TRANSLATION

THE STRUCTURE OF A DETONATION FRONT IN GASSES

By

B. V. Voytsekhovskiy, V. V. Mitrofanov,
and M. Ye. Topchiyan

FOREIGN TECHNOLOGY
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Pages 1-168

TABLE OF CONTENTS

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH

DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

The problem of detonation has long attracted the attention of investigators. Up to the present time there have been widely used only condensed explosives; however, it is possible that in the very near future also gas detonation will find applications which are important in practice. Interest toward detonational processes in gasses is increasing due to the appearing possibilities of realization of steady-state conditions. The study of the structure of a gas detonation permits us to better understand processes in condensed explosives, the investigation of which is considerably more difficult.

One-dimensional theory of detonation is presented in completed form in the book of Ya. B. Zel'dovich and A. S. Kompaneyets: "Theory of Detonation." Further investigations only expand the area of considered phenomena to various degrees. At the same time, in recent years there have appeared a large number of works showing that the actual detonation front in gasses contains strong transverse perturbations; i.e., the structure of this front is essentially three-dimensional.

The purpose of the present book is to present results of investigations of the structure of transverse perturbations of the actual detonation front in gasses. As the basic material there served authors' works conducted first in the Moscow Physical and Technical Institute, and then in the Institute of Hydrodynamics of the Siberian Branch of the Academy of Sciences of the USSR.

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In the introduction to this book there is given a short historical survey of the most well known works on gas detonation. In view of the importance of the one-dimensional theory for description of processes of detonation, in Chapter I there is presented the contemporary state of this question. In Chapter II there are given results of investigations of spin detonation. On the basis of obtained experimental material there is presented a scheme of analysis of flow in the region of discontinuity of the leading front. Here there are considered acoustic oscillations in detonation products and their relation with the structure of the front.

Chapter III is dedicated to the account of experiments and theoretical calculations connected with observation of heterogeneities in a gas detonation front far from the limits. In Chapter IV there is described a method of obtaining stationary detonation in an annular channel. In the last chapter, Chapter V, there are considered general characteristics of behavior of transverse waves during gas detonation and their influence on averaged characteristics of the detonational wave.

The present book was written on the initiative of academician M. A. Lavrent'yev, who gave much attention to investigations of the authors on the given question.

The authors also consider it their duty to thank academician Ya. B. Zel'dovich, R. I. Soloukhin, L. V. Ovsyannikov and S. S. Khlevnyy for their advice and consultations on certain questions presented in the book. Results of V. V. Pukhnachev for the study of instability of a plane detonational wave are presented by our request by the author. During carrying out of the experiment, much work was conducted by B. Ye. Kotov, V. A. Tatarchuk, V. A. Subbotin and P. N. Nikitin.

INTRODUCTION

Development of theory and experiment in questions of explosive processes was considerably advanced when in 1881 Mallard and Le Chatelier [1, 2] and independently of them Bertelot and Vieille [3, 4] established that during igniting of an explosive gas mixture the zone of burning in certain cases propagates with a speed hundreds of times greater than the speed of normal burning of the given mixture. The newly discovered process was distinguished by a number of characteristic properties: speed of propagation exceeds speed of sound; its magnitude is not influenced by change of pressure; above certain minimum sizes, it is not influenced by diameter of pipe; it is not influenced by small additions of foreign matter or method of initiation. Further investigations showed that for a given type of mixture, the speed of detonation, as such a process was called, is a physicochemical constant which little depends on initial state of gas mixture.

First attempts to explain given phenomenon were made by Bertelot and Vieille. They assumed that during propagation of a detonation wave, the main role is played by transport processes. However, even then investigators assumed that with such propagation of the flame a large role must be played by processes of compression in the detonation wave. Thus, there appeared works of Dixon [5, 6, 7], in which ideas of Bertelot and Vieille were combined with the idea of influence

of a sound wave. But the theories of these scientists, as a rule, did not give satisfactory agreement with experiment.

In 1899 Chapman [8] approached detonation from the thermodynamic point of view and calculated its speed, assuming that it was the minimum possible speed. In 1905-1906 Jouget, independently of Chapman, using the conservation laws and considering the entropy of the process, showed that the latter attains a minimum at the point on the Hugoniot curve which corresponds to transonic speed of reaction products relative to the detonation wave front [9, 10]. This point was postulated by him as determining the speed of detonation and the state of the reaction products. Somewhat later, Crussard [11] showed the equivalence of the hypotheses of Chapman and Jouget.

The obtained solution, in spite of its lack of theoretical foundation, gave good agreement with experimental results. A large number of measurements of speed of detonation, performed by the many different authors, gave values which consistently agreed with calculations of Jouget. However, the Chapman-Jouget theory did not explain a number of phenomena and, most important, the limits of detonation.

This prompted a whole series of attempts by scientists (up to 1940) to explain the phenomenon from other initial data. An example of such an approach is the attempt of Lewis [12] to calculate speed of detonation on the basis of diffusion of active centers, in connection with the theory of chain reactions appearing at that time.

In 1940 there appeared the work of Zel'dovich [13], in which there was for the first time given a rigorous foundation for selection of the point on the Hugoniot adiabat which determines the detonation process. Detailed discussion of theories of Chapman-Jouget and Zel'dovich will be conducted in the First Chapter.

In subsequent years and at the present time, development of the

theory of gas detonation was conducted and is being conducted basically in three directions. First, there are efforts to introduce a series of generalizing circumstances, to consider the influence of diffusion, thermal conduction, the possibility of ignition of a mixture with the help of chemically active particles which penetrate into a cold mixture from the reaction zone; there are being analysed detonational processes for the case of a large number of chemical reactions, and there are also being conducted calculations for separate specific cases with given parameters. The second direction is connected with the appearance of nonuniformity of the luminosity of the front during gas detonation in practically all cases observed in experiment. A natural result of this was the formulation of the problem of stability of a one-dimensional detonation process with finite chemical reaction zone. This question was discussed by K. I. Shchelkin [14], R. M. Zaydel' [15] and V. V. Pukhnachev [16]; conclusions obtained by these authors show that under certain conditions such a process has instability.

The third direction appeared in connection with works of Manson [17, 18], Fay [19] and Chu Boa-Teh [20], which show the relation between phenomena after the gas detonation front and acoustic characteristics of the burning gas.

Parallel to the development of the theory, there were conducted a huge number of experimental investigations. Already quite early experiments have shown that attempts to give a complete theoretical foundation of the process within the framework of one-dimensional theory do not explain all phenomena connected with detonation.

The first blow to concepts of detonation as a one-dimensional process was inflicted in 1926 by works of Campbell and his colleagues [21], when there was revealed the phenomenon of spin detonation. Detailed investigations conducted by them, and also by Bone, Fraser and

Wheeler [22], showed that in certain mixtures there is disturbed the uniformity of the detonation wave, and there appears a brightly luminous region rotating around the axis of the tube. Later works established that spin, as this phenomenon was called, appears in all cases when detonation occurs near the limits, independently of the type of mixture and method of approach to the limit. With departure from the limits there is observed so-called many-headed spin.

By further investigations it was revealed that the one-dimensional regime of propagation of detonation in gas mixtures cannot be observed at all under usual conditions.

In the works of Troshin and Denisov [23] it was established that a detonation wave in a gas, even under conditions far from the limit, leaves on the sooty walls of the tube traces of transverse disturbances. These experiments were conducted with mixtures of hydrogen with oxygen, which are considered "classical" from the point of view of uniformity of the detonation wave.

Nonuniformities of the detonation front in gas mixtures were also registered by the optical method by the authors of the present work [24].

It is noteworthy that analogous phenomena were revealed by A. N. Dremin and O. K. Rozanov [25] in liquid explosives.

Various attempts to give an explanation of spin detonation have been made from the time of its discovery. The most widely known is the hypothesis of K. I. Shchelkin [26], who proposed that the detonation process is carried out by the discontinuity of the leading front. The theoretical foundation of this hypothesis was given by Ya. B. Zel'dovich [27].

In 1950 A. N. Voinov [28] expressed his view that due to the delays of ignition of gas after the shock wave front, there can appear a

transverse detonation wave. However, this assumption was not substantiated either by theoretical calculations or experimental results.

In 1957 one of the authors, on the basis of much experimental material, proposed a scheme of flow with a transverse wave [29]. It obtained further development in the work of 1962 [30]. Application of the method of total compensation (see Chapter II) for the first time made it possible to photograph the actual picture of flow in the neighborhood of the transverse wave. Investigations showed that even during detonation far from the limits there exist transverse waves whose structure in principle does not differ from that of the spin wave (see Chapter III).

Along with development of the theory of phenomena of the front, a number of authors made attempts to explain the appearance of nonuniformities by the influence of acoustic oscillations in the burning gas. First Manson [17], and then Fay [19] and Chu Boa-Teh [20] performed calculations of frequencies of such oscillations which gave results coinciding well with experiment. However, the acoustic theory cannot give a full explanation of phenomena in the detonation front. Solution of the problem lies in joint consideration of transverse detonation waves and acoustic oscillations in reaction products excited by them.

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Pages: Cover-168

CHAPTER I

ONE-DIMENSIONAL THEORY OF GAS DETONATION

Definition of Cyrillic Item

равн = eq = equilibrium

Application of the conservation laws to a flow of gas passing through a shock wave in the absence of transport phenomena (viscosity, diffusion and thermal conduction) gives three equations which relate pressure, density and speed of gas relative to the shock:

continuity equation –

$$\rho_0 u_0 = \rho_1 u_1; \tag{1.1}$$

equation of conservation of momentum –

$$p_0 + \rho_0 u_0^2 = p_1 + \rho_1 u_1^2; \tag{1.2}$$

equation of conservation of energy –

$$I_0 + \frac{u_0^2}{2} = I_1 + \frac{u_1^2}{2}. \tag{1.3}$$

Here I_0, I_1 – enthalpy (heat content) of gas per unit mass. It is a function of p and ρ;

u_0 and u_1 – speeds of gas relative to shock;

ρ_0 and ρ_1 – densities of gas;

p_0 and p_1 – pressure before shock wave and behind it.

Elimination from the equations of velocities gives a relationship between enthalpy, pressure and specific volume of gas, which is known by the name of Hugoniot adiabat:

$$I_1(p_1, v_1) - I_0(p_0, v_0) = \frac{p_1 - p_0}{2}(v_0 + v_1). \tag{1.4}$$

Here v is specific volume of substance, which is introduced as

$$v = \frac{1}{\rho}.$$

Together with the equation of state, the Hugoniot adiabat determines the set of parameters p_1, v_1, u_1 after the shock wave front, under the condition that initial state p_0, v_0 and speed of gas u_0 flowing in the shock wave are given. In Fig. 1 there is given the Hugoniot adiabat.

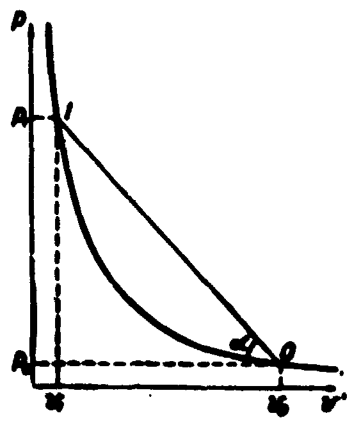

Fig. 1. Hugoniot shock adiabat.

Let us assume that the gas is transferred from state p_0, v_0 by shock compression into state p_1, v_1 (see Fig. 1). Let us connect by a straight line the two points of the Hugoniot curve, determined by these states. Tangent of angle of slope of this straight line obviously satisfies the relationship

$$\operatorname{tg}\alpha = \frac{p_1 - p_0}{v_0 - v_1}. \tag{1.5}$$

On the other hand, by replacing in equations (1.1) and (1.2) density by specific volume and eliminating u_1, we obtain

$$u_0^2 = v_0^2 \frac{p_1 - p_0}{v_0 - v_1}. \tag{1.6}$$

The last equation determines a straight line in plane (p, v) connecting points 1 and 0. Equation of this straight line was obtained for the first time by Michelson [1, 2, 3, 4] and is known in our literature by the name of "Michelson's line," which we will call it subsequently.* It is easy to see that Michelson's line determines speed of gas flowing in shock wave. From equations (1.5) and (1.6) we have

*In the foreign literature this straight line is known by the name of "Rayleigh's line," although Michelson used it for investigation of stationary one-dimensional flow in 1890, i.e., several years before Rayleigh.

$$u_0^2 = v_0^2 \operatorname{tg} \alpha.$$

Rise of temperature for an ideal gas with $\gamma = \frac{c_p}{c_v}$ = const which is compressed by a shock wave is determined by relationship

$$\frac{T_1}{T_0} = \frac{p_1}{p_0}\left[\frac{(\gamma+1)p_0 + (\gamma-1)p_1}{(\gamma+1)p_1 + (\gamma-1)p_0}\right]. \tag{1.7}$$

As can be seen from this relationship, with increase of pressure, drop in temperature behind the front increases. Calculations show that for a speed of the shock wave near 1,700 m/sec in a diatomic ideal gas with molecular weight of 29, the temperature reaches approximately 1,700°K. Such temperatures are more than sufficient for ignition of explosive gas mixtures.

Let us consider a gas containing the chemical energy Q per unit of mass, which upon ignition is released in the form of heat. On the (p, v)-diagram combustion corresponds to the transition to a Hugoniot adiabat, lying above the adiabat for the initial products. Actually, the shock wave with chemical reaction will be described by the same laws of conservation of mass and momentum. The difference is that in the case of the chemical reaction, in the process of transition there is additionally imparted quantity of heat Q to the gas. Equation of conservation of energy (1.3) will therefore have the form

$$i_0 + \frac{u_0^2}{2} + Q = i_1 + \frac{u_1^2}{2}. \tag{1.3'}$$

Hugoniot equation taking into account heat release gives

$$i_1(p_1, v_1) - i_0(p_0, v_0) = \frac{p_1 - p_0}{2}(v_0 - v_1) + Q. \tag{1.8}$$

Inasmuch as enthalpy of an ideal gas is determined by relationship

$$i(p, v) = \frac{\gamma}{\gamma - 1} pv, \tag{1.9}$$

we obtain for an ideal gas with chemical reaction

$$\left(\frac{\gamma+1}{\gamma-1} v_1 - v_0\right) p_1 - \left(\frac{\gamma+1}{\gamma-1} v_0 - v_1\right) p_0 = -2Q. \tag{1.10}$$

For a shock wave, for those same p_0, v_0 and v_1, we have

$$\left(\frac{\gamma+1}{\gamma-1}v_1 - v_0\right)p_1' - \left(\frac{\gamma+1}{\gamma-1}v_0 - v_1\right)p_0 = 0. \tag{1.11}$$

Subtracting (1.11) from (1.10), we obtain

$$\left(\frac{\gamma+1}{\gamma-1}v_1 - v_0\right)(p_1 - p_1') = 2Q.$$

Inasmuch as the first parentheses is always positive,* we have

$$p_1' < p_1,$$

i.e., the Hugoniot adiabat with heat release lies above the shock adiabat.

Let us consider the (p, v)-diagram for these two adiabats (Fig. 2). Depending upon position of the Michelson line, which determines the rate of the process, the Hugoniot adiabat corresponding to the process with heat release is divided into several parts. Velocity is determined from (1.6) as

$$u_0 = v_0\sqrt{\frac{p_1 - p_0}{v_0 - v_1}}.$$

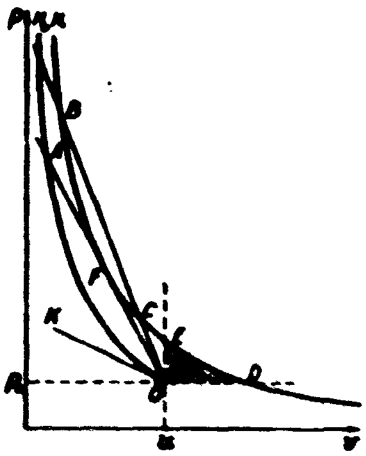

Fig. 2. Hugoniot adiabats with heat release.

On segment ED the quantity $\frac{p_1 - p_v}{v_0 - v_1} < 0$, which leads to an imaginary value of speed of propagation of the process; therefore, transition into states formed by segment of Hugoniot curve ED does not have physical meaning for steady-state regimes. The section below point D corresponds to combustion with increase of specific volume and lowering of pressure; this is the section of regimes of usual combustion, and in our work we will not be interested in this region.

The region above point E describes combustion with increase of pressure and decrease of specific volume; this corresponds to denotation

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*Limiting compression for a single shock transition is determined by relationship $v_0 = \frac{\gamma + 1}{\gamma - 1} v_1$.

processes.

It is known that at point p_0, v_0 the Hugoniot adiabat is tangent to the Poisson adiabat; consequently, the tangent to the Hugoniot adiabat at point p_0, v_0 has a slope, the tangent of the angle of which determines the speed of sound. As can be seen from Fig. 2, the slope of this straight line at point p_0, v_0 is always smaller than slope of the straight line drawn at any point of curve H_1, lying above E. Therefore, speed of propagation of the process corresponding to such points is always greater than speed of sound in the initial gas. From what has been said, it follows that regimes which transfer the gas into states corresponding to sections of the Hugoniot curve above point E determine the process of supersonic propagation of flame, which is accompanied by increase of pressure and decrease of specific volume.

Thus, Hugoniot curve H_1 above point E determines a set of regimes of detonation combustion with speeds $D = u_0$ which do not contradict the laws of conservation (as we will subsequently designate the velocity of detonation), which, in turn, are determined by angles of inclination of Michelson lines connecting point of initial state p_0, v_0 with point of final state p_1, v_1.

It is possible to see that such transitions describe any regimes from some D_{min}, which corresponds to tangency of the Michelson line to the Hugoniot adiabat for products (point F), up to $D \rightarrow \infty$. Point F is interesting due to the fact that through it there passes that single Michelson line which uniquely determines the state of the gas after the front for given speed of propagation.

It is experimentally shown that of all possible regimes, detonation chooses for given p_0, v_0 and Q a single one. The three conservation equations plus the equation of state give the relationship between the five unknown parameters u_0 , p_1 , v_1 , T_1 and u_1. For unique

determination of the realized regime it is necessary to define one more equation. The efforts of many authors were dedicated for a long time to the finding of it.

In 1899 Chapman [5] calculated velocity of detonation, assuming that of all possible regimes there is realized the regime with minimum speed of propagation.

In 1906-1907, Jouget proposed to choose for calculations that point on the adiabat of the products, at which speed of gas relative to the front becomes the speed of sound [6, 7].

We will briefly follow his considerations. Along the Hugoniot curve there is satisfied the relationship

$$(v_0 - v)dp - (p_0 + p)dv - 2dE = 0. \tag{1.12}$$

Change of entropy in the gas after the front is determined by expression

$$TdS = dE + pdv. \tag{1.13}$$

From (1.12) and (1.13) it follows that

$$\left(\frac{dS}{dv}\right)_{H_1} = \left(\frac{v_0 - v}{2T}\right)\left[\frac{p - p_0}{v_0 - v} + \left(\frac{dp}{dv}\right)_{H_1}\right]. \tag{1.14}$$

Here $(\frac{dS}{dv})_{H_1}$ is derivative of entropy with respect to volume after the wave front along the Hugoniot adiabat.

Let us consider the point on the Hugoniot adiabat, where $\frac{dS}{dv} = 0$. At this point $(\frac{dp}{dv})_{H_1} = (\frac{dp}{dv})_S$. Differentiating (1.14) once again with respect to v, we obtain

$$\frac{d^2S}{dv^2} = \frac{v_0 - v}{2T}\left(\frac{d^2p}{dv^2}\right)_S. \tag{1.15}$$

For an ideal gas

$$-\left(\frac{dp}{dv}\right)_S = \frac{\gamma p}{v} \tag{1.16}$$

and

$$\left(\frac{d^2p}{dv^2}\right)_S = \frac{d}{dv}\left(-\frac{\gamma p}{v}\right)_S = \gamma(\gamma + 1)\frac{p}{v^2} > 0.$$

Consequently, in compressional wave ($v < v_0$) $\frac{d^2S}{dv^2}$ is always greater than 0, and equation (1.14), which can be written as

$$\frac{p - p_0}{v_0 - v} = \left(\frac{dp}{dv}\right)_S = \frac{\gamma p}{v},$$

determines point of minimum entropy on the Hugoniot adiabat. By multiplying the last expression by v^2 and using (1.1) and (1.2), we obtain

$$\gamma pv = v^2 \frac{p - p_0}{v_0 - v} = u^2. \qquad (1.17)$$

For an ideal gas the speed of sound

$$c^2 = \gamma pv, \qquad (1.18)$$

i.e., at the point of tangency $c^2 = u^2$. Speed of flow relative to the shock is equal to speed of sound in the medium.

Thus, entropy on the Hugoniot adiabat attains a minimum at the point where speed of detonation products relative to the shock is equal to the speed of sound. Jouget selected this point as determining the speed of detonation. Since the Jouget condition is satisfied at the point of tangency of H_1 with the Michelson line, it is clear that the minimum speed selected by Chapman is equivalent to the equality of speed of the products relative to the front to the local speed of sound.

In the laboratory reference system, the motion of particles after the detonation front is directed in the direction of propagation of the process; therefore, the detonation wave in the absence of compression by a piston is accompanied by a rarefaction wave, the front of which is in the Chapman-Jouget plane.

It is possible to show that speed of detonation products relative to the front, for the section of the curve H_1 lying above the Jouget point, is less than speed of sound in the products, and for the section below the Jouget point, is larger. If we imagine detonation with speed, greater than that determined by the condition $u = c$, then (inasmuch as for sections of adiabat H_1 lying above F the speed of the

products is less than speed of sound) the rarefaction wave, propagating through the detonation products, will overtake the shock front and lower the pressure, thereby, lowering speed of detonation to a minimum. Thus, there is proven the impracticability under normal conditions of regimes above point F.

The elimination of transitions corresponding to the lower intersection points of the Michelson line with the Hugoniot adiabat (point C in Fig. 2), turned out to be impossible within the framework of the given theory.

In the considered theory there was not considered finiteness of width of the chemical reaction zone, and it was tacitly assumed that in the detonation wave there occurs instantaneous chemical transformation. Thus, there was not at all explained the phenomenon of limits of detonation, and, even less, their change with small additions, which, without changing speed of detonation, lead to strong change of its limits (as, for instance, additions of hydrogen to a mixture of carbon monoxide with oxygen).

In spite of these deficiencies, the Chapman-Jouget hypothesis has obtained wide acknowledgement, inasmuch as in practically all cases experimentally measured speeds give good agreement with those calculated according to Chapman-Jouget. At the same time, weaknesses of this theory have served as a constant source of attempts to somehow explain the uniqueness of normal regimes of detonation. Examples of such attempts can be seen in works of Becker [8], Scorah [9], Iost [10] and others, which, however, did not essentially advance the solution of this problem.

The problem of selection of detonation regime was solved by Ya. B. Zel'dovich during consideration of chemical reactions occuring after

the detonation wave front [11, 12, 13].*

Zel'dovich investigated equations of gas dynamics jointly with equation of chemical kinetics of the form

$$\frac{d\beta}{dt} = \beta^m p^{m-1} e^{-\frac{E}{RT}}. \tag{1.19}$$

Here β – weight fraction of unreacting substance;

E – activation energy; m – order of reaction.

Considering forces of deceleration and heat radiation, he showed that the only possible nontrivial steady-state solution of such a system satisfying to boundary conditions leads to the following picture of flow after the front:

1) specific volume of gas after compression in the shock wave is continuously increased;

2) the pressure drops;

3) speed of gas relative to the front increases, becoming the speed of sound at the place where rate of heat emission becomes equal to rate of heat losses.

Let us expound here the basic results of the theory of Zel'dovich, taking into account later works.

Let us consider one-dimensional detonation wave in ideal gas with constant specific heat ratio γ. In theory of Zel'dovich such a wave is a complex consisting of a shock discontinuity, which shifts the gas from state 0 into state A (see Fig. 2), and a zone of chemical reaction following after it. Inasmuch as the process is assumed to be steady-state, the state of reacting gas should be changed along Michelson line AO. The relation between p_0, ρ_0, u_0, I_0 and p, ρ, u

*Later, detonation with finite width of chemical reaction zone was considered by Von Neumann [14] and Döring [15]; however, neither could give an estimate of the role of losses during detonation processes.

and I on any control surface in zone of reaction is described by equations (1.1), (1.2), (1.3) and (1.9), where quantity of heat released in process of reaction can be considered as a parameter. Let us introduce dimensionless variables

$$\left.\begin{aligned} \sigma &= \frac{\rho}{\rho_0}, \\ \pi &= \frac{p}{p_0} \\ M &= \frac{u}{c} = \frac{u}{\sqrt{\frac{\gamma p}{\rho}}}. \end{aligned}\right\} \qquad (1.20)$$

and

From equations (1.1), (1.2), (1.3), (1.9) and (1.20), quantities σ, π and M can be expressed as functions of u_0, c_0 and Q:

$$\sigma_{1,2} = \frac{c_0^2 + u_0^2\gamma \pm \sqrt{(u_0^2 - c_0^2)^2 - 2(\gamma^2 - 1)u_0^2 Q}}{2c_0^2 + (\gamma - 1)(u_0^2 + 2Q)}, \qquad (1.21)$$

$$\pi = \gamma\frac{u_0^2}{c_0^2}\left(1 - \frac{1}{\sigma}\right) + 1; \qquad (1.22)$$

$$M^2 = \frac{1}{\gamma\left[\sigma\left(1 + \frac{c_0^2}{\gamma u_0^2}\right) - 1\right]}. \qquad (1.23)$$

Equations (1.21), (1.22) and (1.23) determine a family of Hugoniot curves with parameter Q (Fig. 3). For Q = 0 this is shock adiabat H_0, passing through point of initial state (σ = 1, π = 1).

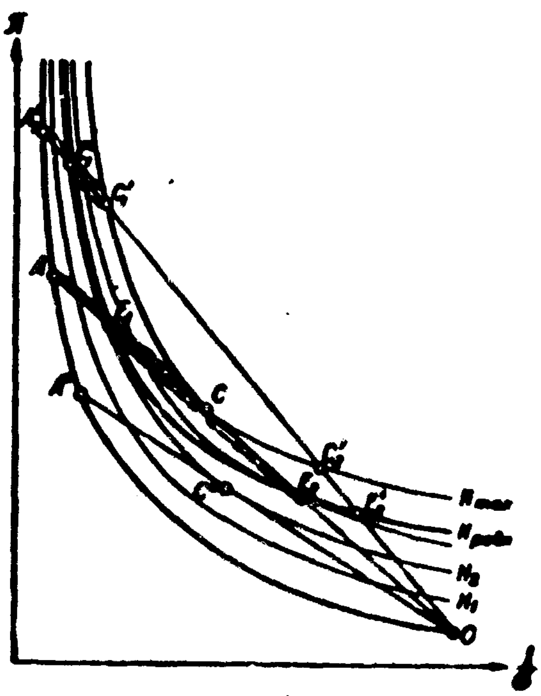

Fig. 3. (p, v)-diagram of steady-state detonation processes.

The expression under the radical in equation (1.21) must be non-negative; therefore, for given value of u_0, quantity of heat released in one-dimensional stationary flow cannot exceed a certain value Q*, which is a function of u_0:

$$Q < Q^*(u_0) = \frac{(u_0^2 - c_0^2)^2}{2(\gamma^2 - 1)u_0^2}. \qquad (1.24)$$

Let us consider also the family of Michelson lines. Every such straight line is described by equation (1.22); angle of inclination of it depends on value of u_0. In accordance with the double sign in equation (1.21), for any selected pair of quantities u_0 and $Q < Q^*(u_0)$ we have two solutions determining two intersection points of Michelson line with Hugoniot adiabat for the given Q. Sign "plus" corresponds to the upper point of intersection; "minus " sign – to the lower.

On every straight line, for instance A"O, Q changes from zero on H_0 to $Q^*(u_0)$ at point of tangency C" of the given straight line with corresponding adiabat H_2. By substituting $Q = Q^*$ in equations (1.21), (1.22), (1.23), we obtain for the point of tangency:

$$\sigma_1 = \sigma_2 = \frac{(\gamma + 1)u_0^2}{c_0^2 + \gamma u_0^2}; \qquad (1.25)$$

$$\pi = \frac{\gamma}{\gamma + 1}\left(\frac{u_0^2}{c_0^2} - 1\right) + 1; \qquad (1.26)$$

$$M = 1. \qquad (1.27)$$

From equation (1.21) it is clear that at upper point of intersection of given Michelson line with any adiabat H_1 on which $Q < Q^*(u_0)$, $\sigma_1(Q) > \sigma(Q^*)$, at the lower point $\sigma_2(Q) < \sigma(Q^*)$.

Since for $\sigma = \sigma(Q^*)$, $M = 1$, from equation (1.23) it follows that at the upper point $M_1 < 1$; i.e., flow is subsonic. At the lower point $M_2 > 1$; i.e., the flow is supersonic.

Thus, for motion along every Michelson line in the direction from the shock front, Mach number increases, attaining unity at the point where $Q = Q^*(u_0)$, which coincides with point of tangency of the given straight line to the Hugoniot adiabat. From equation (1.21) it follows that such a point on every straight line is unique; otherwise, for

certain values of u_0 and Q there would be more than two solutions, Below the point of tangency flow becomes supersonic; thus, heat should be absorbed, and pressure should drop.

In a detonation wave, liberation of heat as a result of chemical reaction occurs by laws determined by equations of chemical kinetics. If equations of all occurring reactions are known, then, by using relationships considered here, it is possible in principle to always express change of Q, π, σ and T along any Michelson line as functions of only one time t in a particle of gas, which is measured from the moment of passage of the given particle through the shock front.

We will consider the case when law of heat emission has the form depicted in Fig. 4.*

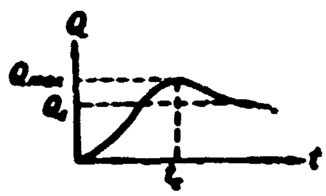

Fig. 4. Curve of heat emission with maximum.

Quantity of released heat attains a maximum, then starts to decrease in virtue of thermal losses or the specific character of the mechanism of reaction. If losses are absent (in practice they can always be disregarded during detonation in sufficiently wide pipes), then maximum liberation of heat Q_{max} may coincide with equilibrium.

Zel'dovich showed [11, 12] that steady-state regime of detonation is always determined by quantity Q_{max}. If we connect on all Michelson lines points at which there is attained Q_{max}, then we can obtain the adiabat of "maximum heat emission" H_{max} (see Fig. 3). The thus constructed adiabat ends at some extreme Michelson line AO, such that on the lower straight lines the quantity of heat separated in the course of reaction exceeds the largest permissible for stationary flow with

*By Q here there is understood the quantity of heat, decreased by the magnitude of heat losses, which would be released at constant volume if molar composition of the reagents turned out to be the same as at the given point of the detonation wave.

these speeds. In general Q_{max} along various Michelson lines do not coincide, and at the end point C of adiabat H_{max} can approach straight line AO at an angle different from zero.

We will at first consider that Q_{max} does not depend on temperature and pressure of gas; then adiabat of maximum heat emission H_{max} will coincide with one of the adiabats Q = const. Let us distinguish also the adiabat with $Q < Q_{max}$, which is attained after passage through the maximum. For reactions without losses, in which the maximum is due to peculiarities of kinetics, at the last it is possible to take the equilibrium adiabat H_{eg} (see Fig. 3).

Let us designate by D_c the speed of detonation corresponding to the tangency of the Michelson line to adiabat H_{max}. Let us consider a detonational process with speed $D > D_c$. With liberation of heat in the course of chemical reaction, state of gas will change along a certain straight line $A'O$ which intersects curve H_{max} at point C_1'. When Q changes from 0 to Q_{max}, the state of the reacting gas is displaced from A' to C_1'; thus, at point C_1', in accordance with equation (1.23), Mach number $M < 1$, since on this straight line $Q^* > Q_{max}$. If after reaching point C_1' in stationary flow Q decreases, then pressure and density of gas have to be displaced along the same straight line in the opposite direction, for instance up to equilibrium point E_1'; then Mach number decreases.

It is clear that stationary detonation wave with speed $D > D_c$ should be artificially sustained by motion of piston with speed $D\left(1 - \frac{1}{\sigma_1}\right)$ in motionless system of coordinates, where σ_1' is relative compression at point of final state. Otherwise, the appearing rarefaction wave will overtake the shock front and will cause its deceleration, inasmuch as the flow is everywhere subsonic. Such detonation is called

supercompressed. Points C_2' and E_2', which correspond to "weak" regimes of detonation on this straight line, are unattainable, since for this there would be required release of heat larger than the maximum possible.

Let us imagine now that speed of piston, maintaining supercompressed detonation wave slowly decreases, so that at every moment of time flow can be considered to be stationary. Michelson line depicting such a process will constantly rotate in the direction of smaller D. When it coincides with the tangent to adiabat H_{max} at point of tangency C, Mach number will attain unity. At all remaining points the flow remains subsonic. Distribution of quantity $\pi = \frac{p}{p_0}$ and $M = \frac{u}{c}$ for this case is depicted in Fig. 5 by the dashed line. Obviously, further deceleration of piston will not change flow before point C, since at this point M = 1 and the rarefaction wave cannot overtake the shock front.

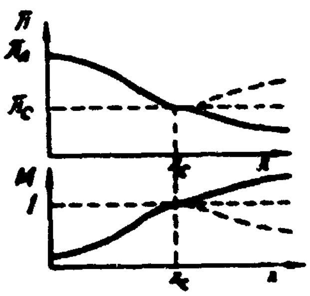

Fig. 5. Distribution of pressure and Mach number of flow behind the front for two possible regimes of detonation.

On straight line AO, $Q = Q_{max}$. On Michelson lines lying below (A"O), $Q^* < Q_{max}$, i.e., in the reaction there is released more heat than the steady-state regime allows, and, therefore, steady-state detonation with speeds $D < D_c$ is impossible. Thus, we arrive at unique selection of speed of the independently propagating steady-state detonation wave. It is determined by the slope of the tangent to the adiabat of maximum heat emission. At point of tangency C (see Fig. 3) $Q_{max} = Q^*$, $D = D_c$; then from equation (1.24) we obtain a formula for determination of speed of detonation:

$$\frac{(D^2 - c_0^2)^2}{2D^2(\gamma^2 - 1)} = Q_{max}. \tag{1.28}$$

For $D^2 \gg c_0^2$ we have the known approximate formula

$$D = \sqrt{2(\gamma^2 - 1)\, Q_{max}}. \qquad (1.28a)$$

In the space behind a plane shock front leading the detonation wave, the surface on which there is attained M = 1 is also plane. It is called the Chapman-Jouget plane. The course of change of all quantities between shock front and Chapman-Jouget plane is uniquely determined by equations (1.21), (1.22), (1.23) and dependence Q(t). Dependency on x of the distance passed over by a particle from the shock front can be obtained if t is expressed in terms of x from equation

$$x = \int u(t)\, dt = \int \frac{D}{\varkappa[Q(t)]}\, dt.$$

Dependences p(x), ρ(x), T(x) for a reaction of type (1.19) according to Ya. B. Zel'dovich and A. S. Kompaneyets [13] have the form depicted in Fig. 6.

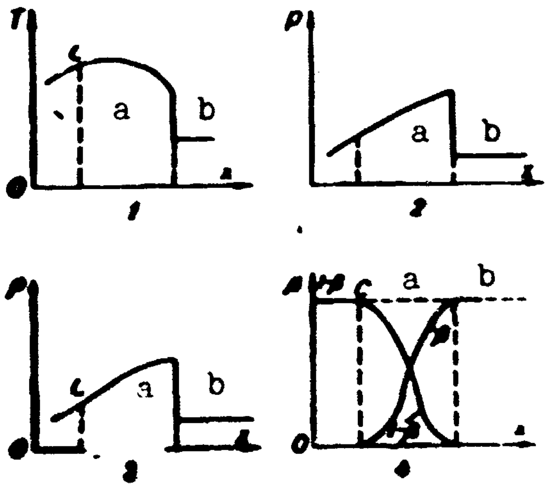

Fig. 6. Distribution of parameters in a detonation wave according to Ya. B. Zel'dovich and A. S. Kompaneyets [13]. 1) temperature; 2) pressure; 3) density; 4) course of the reaction; a) zone of reaction; b) initial mixture.

If after achievement of maximum Q decreases, then behind the Chapman-Jouget plane equations (1.21)-(1.23) give two possible flows:

1) pressure and density are increased along straight line AC from point C upwards, as is shown by the arrows in Fig. 3;

2) pressure and density drop along the same straight line from point C downwards.

As it was shown, flow of the first type can be realized only by motion of a piston with appropriate speed. In the absence of a piston, the rarefaction wave will make the flow after the Chapman-Jouget plane non-stationary. However, if we consider the flow between

Chapman-Jouget plane and a certain surface located at a fixed distance downstream from it, then with passage of time it will approach the stationary flow described by formula (1.21) with the "minus" sign together with (1.22) and (1.23) for decreasing Q.

During propagation of a steady-state detonation wave in a pipe, the presence of a maximum of Q is explained by the fact that at a certain distance from the shock front heat radiation into the walls starts to predominate over liberation of heat in the course of the chemical reaction. Therefore, in a sufficiently long pipe, between the two indicated surfaces there should be produced a practically stationary supersonic zone, in which pressure profile and distribution of other parameters are determined only by losses on the walls and residual chemical reactions.

Let us indicate an example from which the possibility of a stationary zone after the Chapman-Jouget plane is evident. Let us assume that the detonation tube is destroyed after passage of the detonation wave at a certain constant distance from the Chapman-Jouget plane, as shown in Fig. 7.

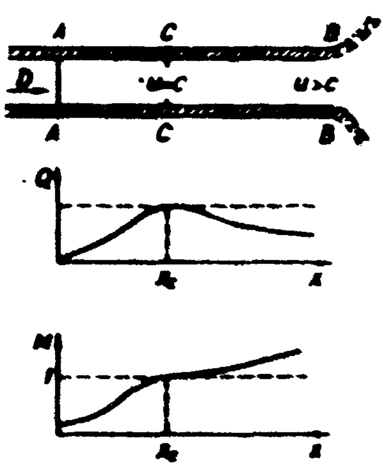

Fig. 7. Example of supersonic stationary zone after the Chapman-Jouget plane.

Here AA is shock front, CC is Chapman-Jouget plane, BB is place of break of tube. In a system of coordinates connected with the front we will have free outflow of the reacting gas from end of the tube. The mixture proceeds through plane AA with parameters produced by the shock wave. The whole flow will be stationary, with critical speed u = c in Chapman-Jouget plane CC. If external pressure is sufficiently low, then absorption of heat after the critical section due to withdrawal of heat into the walls or, for

instance, delayed dissociation will make the flow supersonic. If now, starting from a certain moment of time, detonation passes into a tube with stronger walls, which cease to be destroyed, stationary supersonic zone not only will be retained, but will be increased, with speed u - c at its end.

When in the supersonic stationary zone there is attained chemical equilibrium, the state of gas in it in the absence of losses will be determined to be lower than the intersection point of Michelson line AO with equilibrium Hugoniot adiabat H_{eg}(point E_2 in Fig. 3). Thus, with respect to the equilibrium adiabat, weak detonation is realizable.

K. I. Shchelkin [15] tried to prove the unattainability of point E_2 in a stationary detonational wave by the fact that during the transition from point E_1 to point E_2 there decreases entropy of the gas. However, he did not consider change of the mixture composition during such a transition; therefore, the entropy considerations given by him are inaccurate. Entropy in zone of reaction, of course, should continuously increase with distance from the shock front. During change of mixture composition this is possible even if Q decreases.

The above-stated theoretical results, in which there are used the conclusions of usual gas dynamics for nonreacting systems, recently were subjected to considerable reconsideration. The fact is that speed of sound in the reacting medium is not determined simply by assignment of p, ρ and γ, but depends also on mixture composition and rates of chemical reactions.

It is possible to consider two extreme cases. First — during the time of passage of the disturbance created by the sound wave, chemical equilibrium has time to be displaced, and at every given moment of time the composition corresponds to equilibrium at given pressure and

mperature,* i.e., chemical reactions have time to "follow" the changes external conditions. This corresponds to zero change of free energy Speed of sound in this case is "equilibrium" and is defined as

$$c_e^2 = \left(\frac{\partial p}{\partial \rho}\right)_{S,\, \Delta F=0}. \tag{1.29}$$

The second limiting case – change of pressure in sound wave occurs fast that it does not have time to cause noticeable displacement of uilibrium; mixture composition remains constant. Such a process determines "frozen" speed of sound, corresponding to formula

$$c_f^2 = \left(\frac{\partial p}{\partial \rho}\right)_{S,\, \gamma_i}. \tag{1.30}$$

The derivative is taken at constant entropy and mixture composition. For an ideal gas the last expression coincides with (1.17), if is calculated for the given fixed composition.

The fundamentals of gas dynamics of reacting systems, in particular application to questions of gas detonation, were developed by W. W. od and J. Kirkwood [17-21]. The most controversial was the question ncerning for what speed of sound the Jouget condition should be tisfied. It was shown [22] that always

$$c_f > c_e,$$

ere the equality sign holds only in an exceptional case.

It is clear that to talk about the equilibrium speed of sound has aning only if the disturbance propagates through the equilibrium itial state of the mixture. This case is the most important in actice. Although speed of detonation is determined not by the uilibrium, but by the "maximum" liberation of heat, during calculations it is necessary to use the equilibrium adiabat, since kinetic uations of all reactions under conditions of the detonation wave are

*Here, as everywhere in the book, we speak of chemical equilibrium. lative to local thermodynamic equilibrium, we will assume that it ists everywhere in the medium.

not known accurately for any mixture, and therefore, it is impossible in practice to construct "maximum" adiabat. Furthermore, maximum of Q, in virtue of kinetic peculiarities, apparently exists only for a few reactions. Among the latter it is now possible to include only $H_2 + Cl_2 \rightleftarrows 2HCl$ [23], for which calculation of speed of detonation on the assumption of equilibrium composition of the products gives at low initial pressures a value which is too low as compared to experiment. Apparently, for the majority of detonating gas mixtures the quantity of heat released in the course of chemical reaction grows monotonically, and maximum of Q is due only to losses. But in the latter case, if the detonation propagates in a sufficiently wide pipe (as compared to the effective width of the reaction zone), at the point of maximum of Q the mixture composition will differ very little from equilibrium, and consequently calculation can be produced according to the equilibrium adiabat. At point of tangency of Michelson line to the equilibrium adiabat there is satisfied the Jouget condition for equilibrium speed of sound [24]; i.e., speed of gas in system of coordinates connected with front is equal to c_e.

For stationarity of the process it is necessary that rarefaction wave could not penetrate beyond the Chapman-Jouget plane and weaken the shock front. It is obvious that if all parameters of the flow (for instance, pressure) change in the rarefaction wave so slowly that at every point of the wave there exists local chemical equilibrium, then each of these points characterized by fixed values of equilibrium parameters (including and its front) will propagate relative to particles of gas with the local equilibrium speed of sound. Consequently, in this case the stationary reactionary zone between shock front and "equilibrium" Chapman-Jouget plane is compatible with the rarefaction wave behind this plane.

However, the real rate of reactions is always finite; therefore, "equilibrium" rarefaction wave corresponds to an infinitely slow change of all parameters, or to an infinitely extended profile of the rarefaction wave, which is attained only as $t \to \infty$. For any finite time from the moment of appearance of detonation, the wave length of the rarefaction wave is also finite, and its front, as S. Brinkley and J. Richardson showed for the first time [25], propagates with "frozen" speed of sound. The rarefaction wave in reacting gas was considered in more detail by V. N. Arkhipov [26]. He showed that although the rarefaction wave front indeed propagates through the initially equilibrium state with frozen speed of sound, the disturbance imparted to it exponentially attenuates, and the main variation of parameters is transferred with equilibrium speed of sound.

Thus, after passage over a sufficiently large path, the independently propagating detonation wave will be practically stationary; speed of its propagation is calculated from the condition of tangency of the Michelson line to the equilibrium adiabat. Everywhere above the point of tangency on the equilibrium adiabat $u < c_e$; consequently, the detonation process corresponding to these points can exist only in the presence of a piston maintaining the process.

In Table 1 there are given results of calculations of Chapman-Jouget states for certain gas mixtures, which were obtained from the condition of tangency of Michelson line to equilibrium adiabat.

It is of theoretical interest to investigate possibilities of stationary supersonic flow after the Chapman-Jouget plane, when the quantity of heat Q released in the reacting flow attains a maximum, and then decreases. Up to the present time the most complete investigation of one-dimensional steady-state regimes after the detonation wave front has been carried out by W. W. Wood and Z. V. Salsburg [22].

Table 1.

Mixtures	D_0 m/sec	γ_f	γ_e	c_f, m/sec	$U_1 = C_e$, m/sec	T_1, K	$\frac{\rho_0}{\rho_1}$	$\frac{p_1}{p_0}$	Source
$2H_2+O_2$	2840	1,217	1,128	1604	1544	3678	0,5436	18,82	[24]
$C_2H_2+2,5O_2$	2426	1,269	1,152	1382	1317	4212	0,5430	33,81	[24]
$2CO+O_2$	1787	1,212	1,120	1021	968	3508	0,542	18,58	Author's calculations

Note: γ_f – "frozen" specific heat ratio; γ_e – "equilibrium" specific heat ratio, determined by formula $c_e^2 = (\gamma_e p/\rho)$; T_1 – temperature; ρ_0/ρ_1 – density ratio; p_1/p_0 – pressure ratio.

In particular, they considered "pathologic detonation," when there is possible transition from stationary subsonic flow to stationary supersonic flow (with respect to "frozen" speed of sound), where at the point of transition, where $u = c_f$, the reaction has still not been completed. For γ = const such a regime corresponds to the case when at the lower point of the adiabat of maximum Q, speed of flow attains "frozen" speed of sound.

In the theory of Zel'dovich there are not considered transport phenomenon. Therefore, amplitude of pressure after the shock wave is determined only by speed of detonation and does not depend on the flow of chemical reactions.

The influence of viscosity, diffusion and thermal conduction on structure of detonation wave was investigated in detail by J. O. Hirschfelder and his colleagues [27, 28, 29]. Although during solution of the problem in these works there are imposed quite strong limitations on properties of the medium, the qualitative results are of doubtless interest.

The process of expansion in the stationary case does not proceed here along a Michelson line. This follows directly from the

Navier-Stokes equation for one-dimensional flow of a viscous compressible medium. In the stationary case it has the form:

$$\rho u \frac{\partial u}{\partial x} = -\frac{\partial p}{\partial x} + \left(\frac{4}{3}\eta + \zeta\right)\frac{\partial^2 u}{\partial x^2}. \qquad (1.31)$$

Here η and ζ are coefficients of viscosity of the medium. Condition of continuity ρu = const makes it possible to integrate the equation once. As a result of integration we obtain

$$\rho u^2 + p = \left(\frac{4}{3}\eta + \zeta\right)\frac{\partial u}{\partial x} + \text{const}. \qquad (1.32)$$

In the absence of viscosity, this equation coincides with (1.2); in the presence of viscosity, the left side of equation (1.32) depends on velocity gradient, and relationship (1.6) is not satisfied.

The most important result of Hirschfelder is that with consideration of transport processes, in general there is not attained state corresponding to the intersection of Michelson line with Hugoniot adiabat for the initial substance (Fig. 8). The stronger the interaction is between shock front and zone of chemical reaction, the less the maximum pressure developed during detonation is.

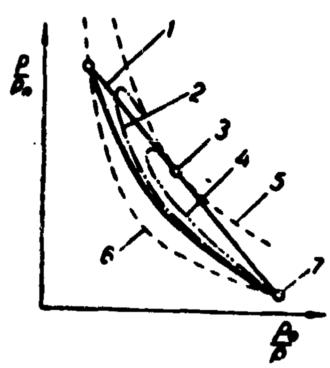

Fig. 8. Detonation transitions, taking into account transport phenomena according to Hirschfelder and others [32]. 1) Michelson-Rayleigh line; 2) course of process for slow kinetics; 3) Jouget point; 4) course of process for fast kinetics; 5) Hugoniot adiabat with heat emission; 6) Hugoniot adiabat for initial substance, 7) point of initial state.

With decrease of interaction, maximum pressure is increased, attaining in the limit the value obtained in the theory of Zel'dovich.

In Fig. 9 there are given dependences obtained by Hirschfelder of parameters of gas and concentration of initial substances in the detonation wave on dimensionless coordinate. Here $\theta = \frac{T}{T_0}$ and x is the relative concentration of initial substance. As we should have expected, with consideration of

transport phenomena the shock wave front is smeared out, and variation of parameters has a continuous character.

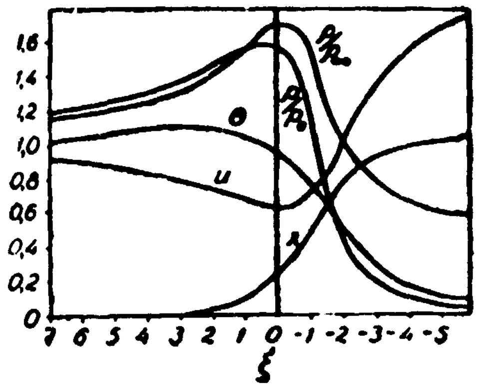

Fig. 9. Profile of detonation wave according to Hirshfelder.

In this chapter there have been considered one-dimensional detonation processes. As we will see subsequently, the real detonation front in gases usually contains transverse perturbations. Nevertheless, one-dimensional theory describes the process well if we do not consider the "fine structure" of the detonation wave. Speeds of detonation, pressures, densities and temperatures after the front calculated according to one-dimensional theory coincide well with experimental data [6, 10, 23, 30-40].

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CHAPTER II

SPIN DETONATION

Definitions of Cyrillic Items in Order of Appearance

Subscripts and Abbreviations

мксек = μsec

$$\frac{\text{см}^2}{\text{сек}^2} = \frac{\text{cm}^2}{\text{sec}^2}$$

уд = sh = shock

дет = det = detonation

Designations of Instruments

ИАБ-451 = IAB-451 [Toepler photography installation]

ОК-25 = OK-25 [oscillograph]

ОК-17М = OK-17M [oscillograph]

РФ-3 = RF-3 [photographic film]

§ 1. Discovery and First Investigations of Spin

The phenomenon of spin detonation was discovered by Campbell and colleagues in 1926 [1, 2, 3]. During the study of phototracings of the process on film there were revealed periodic changes of intensity of exposure of the film (Fig. 10). Detailed investigations soon made it possible to establish that the observed nonuniformities are a result of nonuniformity of the process of explosion in the mixture.

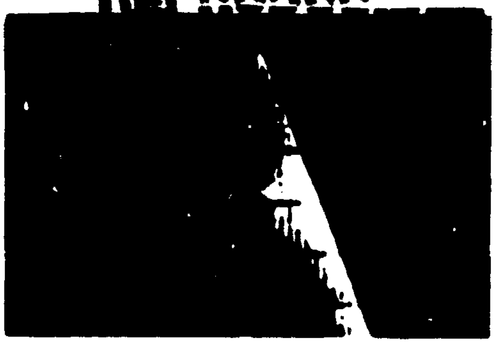


Fig. 10. Spin detonation according to Campbell and others. Scanning of self-luminosity is perpendicular to propagation of the detonation wave.

The first investigations conducted by Campbell and colleagues revealed a series of interesting properties of the new phenomenon. During detonation of carbon monoxide and oxygen there was observed formation of a rotating brightly luminous region localized at the wall-a head. Frequency of rotation of head depended on diameter of tube. Introduction of concentric rod affected frequency, without changing longitudinal speed of propagation of the detonation. Scans of the phenomenon from the end of the tube revealed a cycloid; this confirmed the presence of rotation. Ratio of step of spiral described by the zone of bright luminosity to diameter turned out to be constant, equal approximately to 3.

Investigations of Bone, Fraser and Wheeler [4, 5] confirmed the existence of a rotating region. Upon transition of the detonation from a lead pipe into a glass one, on the internal wall of the latter tube there was revealed a spiral trace formed by a deposit of lead. In a silvered tube, burning of silver occurred along the same spiral. An analogous trace is left during passage of a spin detonation through a sooty tube (Fig. 11).

Fig. 11. Trace of spin detonation on sooty wall of glass tube.

By photographing the detonation through a transverse slot in a

film, moving parallel to the axis of the pipe, Campbell discovered a long luminous band — a trail, which follows after the head. Frequency of rotation of the trail turned out to almost coincide with frequency of rotation of the head.

Later Kh. A. Rakipova, Ya. K. Troshin, K. I. Shchelkin, S. M. Kogarko and others revealed that spin in all cases is observed at the limits of detonation independently of method of approach to the limit [6-12]. Moreover, spin is always observed at the limits of detonation and is apparently the "last possibility" of its propagation.

Very interesting from this point of view are works of Mooradian and Gordon [10, 11]. In these investigations for experiments there was used a shock tube with length of 10 m. Along the tube there were placed pressure transducers of tourmaline. Oscillography was conducted by a multi-channel system. Ignition was produced by a shock wave obtained in a separate section by detonating of an explosive mixture. By changing the pressure of the igniting gas, it was possible to regulate amplitude of the compressive wave propagating through the investigated gas. Registration of the shock wave by transducers made it possible to establish speed of propagation of the process.

In the case when the tested mixture is able to support independent detonation, the compression shock obtained in the igniting section rapidly lowers its speed until the Chapman-Jouget regime is established. If the shock is too weak to generate detonation, its speed rapidly drops to sonic speed. Of doubtless interest is the following: if the igniting shock enters a mixture which lies outside the limits of detonation, but is sufficiently close to them, then, just in the preceding case, the supercompressed wave rapidly attenuates. During transition through the Chapman-Jouget regime the drop of speed is retarded; then there occurs a sharp decrease to a

magnitude close to the speed of sound. At the time of transition through the Chapman-Jouget state there are observed oscillations whose frequency coincides with that calculated for spin. Thus, even in the nonstationary case, during transition through the Chapman-Jouget regime, for a short time there is observed spin.

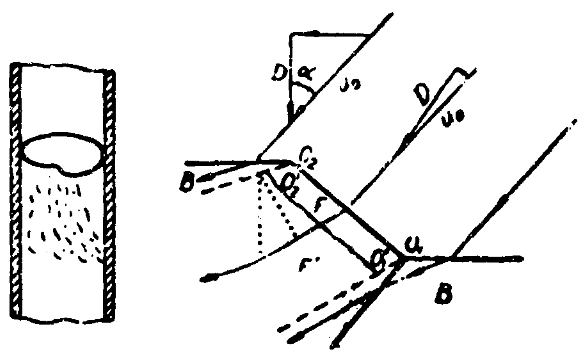
In the experiments of Bone and his colleagues, it was revealed that sometimes spin detonation suddenly changes frequency of rotation by a whole number of times. This phenomenon has received the name of "many-headed" spin. Detailed investigations of this phenomenon showed that with departure from the limits of detonation, the number of rotating zones of ignition is increased.

During investigation of mixtures difficult to detonate, of the type of methane and air, S. M. Kogarko revealed that spin is observed also for very large diameters of the pipe (to 305 mm) [16].

Attempts to explain the phenomenon of spin detonation began at the moment of its discovery and have continued up till now. Initial assumptions of Campbell about rotation of the entire mass of gas were very rapidly refuted in the works of Bone and his colleagues, who discovered that spin is observed in tubes of rectangular and triangular cross sections. They also established that introduction into a detonation tube with diameter of 12 mm of a longitudinal rib with height of 1 mm does not affect process of spin detonation [4, 5].

Becker proposed to explain the spin regime by the fact that the flame front periodically overtakes the shock wave front and then falls behind it, and that this leads to formation of a wavy structure of the scan of self-luminosity [13]. However, such an assumption does not explain the appearance of the spiral trace. Probably the nearest of all to the truth was the assumption of Bone, Fraser and Wheeler, who considered that zone of ignition during spin is advanced forward

in the form of a point describing a spiral trajectory. It is true that the physical meaning of this phenomenon remained vague.



a) b)

Fig. 12. Diagram of fronts during spin detonation of the region of discontinuity according to A. M. Brodskiy, and Ya. B. Zel'dovich.

In 1945 K. I. Shchelkin [14] advanced the assumption that in a shock wave front igniting a gas, there appears a stationary discontinuity accomplishing rotation. Thanks to higher speed, the temperature in the region of discontinuity is increased, and in it there will be formed a seat of ignition. Theoretical proof of the hypothesis of Shchelkin was proposed by Ya. B. Zel'dovich [15, 16]. The general picture of detonation according to the Shchelkin-Zel'dovich theory was assumed to be such as is depicted in Fig. 12a.

The basic idea of such an explanation of the process was that under conditions close to the limit gas compressed by a plane wave reacts slowly. Pressure of compressed gas is larger than at the Jouget point. Therefore, such a gas can play the role of a piston, supporting the supercompressed oblique detonation wave.

Results of analysis of the picture of flow conducted by A. M. Brodskiy and Ya. B. Zel'dovich [17] for a mixture of 15.3% H_2 and air led to the picture of flow in the region of break depicted in Fig. 12b, in a system of coordinates connected with the discontinuity. Here $O_1 O_2$ is oblique detonation wave; $O'_1 O'_2$ is surface of combustion; region B is gas compressed by plane shock wave; region F' is detonation products of the oblique wave; arrows show direction of flow; D_1 is normal velocity of front $O_1 O_2$; u_0 is total velocity of undisturbed flow. Angle α, which is obtained to be equal to 44° (close to the experimental

value), is determined from the condition of equality of total velocity of flow in region F' to the local velocity of sound (otherwise rarefaction wave at point O'_2 will overtake oblique detonation front).

Such a scheme of flow possesses a series of deficiencies. It is not clear how there is maintained the constant dimension of the transverse wave. For transonic speed in region F', it is not clear what causes splitting of the front at point O_1. Furthermore, the scheme has not been sufficiently confirmed by experiment. For such reasons the authors of the present work carried out investigations for more detailed study of the region of break of the front shock front and phenomena connected with formation of the trail of the spin detonation.

§ 2. Investigations of Spin Detonation by Optical Methods

Photoregistration of spin detonation conducted up until recently did not make it possible to investigate the picture of self-luminosity in the region of discontinuity. The method of photoregistration on moving film applied earlier [1-5], due to noncoincidence of speed of the film and speed of motion of the image leads to the obtaining of unclear, smeared-out phototracings. At the same time, stationarity of the process makes it possible to equalize speeds of film and image and to obtain clear pictures of the process.

Such a method was for the first time applied by K. I. Shchelkin and Ya. K. Troshin in 1949. The essence of it is the following: Velocities of film and image of the photographed object have to coincide in magnitude and direction. With such compensation every point of the studied phenomenon is projected only into the one point of the film corresponding to it. During the period of exposure, the film

and the object photographed on it remain motionless relative to one another.

The scheme of experiment can be imagined as if the slot shifts between the film and the object, which remain motionless. However, in experiments of Troshin and Shchelkin there was compensated only the longitudinal component of velocity. During the study of spin, it is necessary to turn the axis of the photorecorder by the angle of the spiral of spin; then the motion of the image will be completely compensated, and the obtaining of clear photographs will become possible [18-20]. The setup of the experiment is shown in Fig. 13.

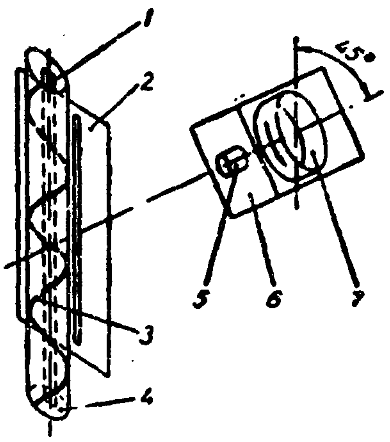


Fig. 13. Photographing of spin by the method of total compensation. 1) axial screen; 2) screen with slot; 3) direction of motion of head; 4) detonation tube; 5) objective; 6) photorecorder; 7) drum.

Magnitude of blurring of the image can be calculated as

$$\Delta x = \tau \Delta v = \frac{hv\sigma}{u \sin \alpha} = \frac{h\sigma}{k \sin \alpha},$$

where $\Delta v = \sigma v$ — residual difference between speeds of film and image;

v — speed of film;

h — width of slot;

u — speed of displacement of process;

$k = \frac{u}{v}$ — reduction factor of objective of photorecorder;

α — angle between direction of motion of image and slot;

σ — relative error in compensation of speed, not exceeding 10%.

Numerical values of these quantities during experiment were: $k = 20$, $h = 1$ mm, $\alpha = 45^{\circ}$. The value of $\Delta x = 1/140$ mm obtained during calculation is far beyond the limits of resolving power of

usual film, and, therefore, cannot make the image worse.

For obtaining total compensation, it is necessary to impart to the film the circular velocity

$$v = \frac{D}{k \cos \alpha}.$$

This can be seen in Fig. 14. Detonation here shifts along the tube with speed D; the head of the spin revolves around the axis; total velocity of the head is equal to $\frac{D}{\cos \alpha}$. Taking into account decrease of the objective of the photorecorder, we obtain the indicated magnitude.

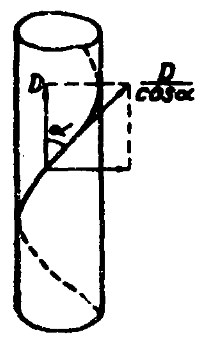


Fig. 14. Determination of speed of total compensation.

By means of the described method of total compensation, there was studied detonation of carbon monoxide and oxygen at stoichiometric composition. Ignition was carried out by a charge of lead azide. Photography was performed at distances from the place of ignition, where the phenomenon took on a stationary character. Direction of rotation of spin was given by a segment of spiral with step of 3 diameters and length of 1.5 turns placed near the place of ignition. Inasmuch as the plane of rotation of the photorecorder was turned in such a manner that motion of film coincided with tangent to spiral trajectory of the "head", then there was carried out total compensation, and there were obtained photographs on which it was possible to examine structure.

Advantages of such a method become clear during comparison of tracings obtained with total compensation and without it. In Fig. 15 there is given a photograph obtained by Bone, Fraser and Wheeler (a) and a photograph obtained by the authors during compensation of only the transverse component, (b), from which it is possible to see

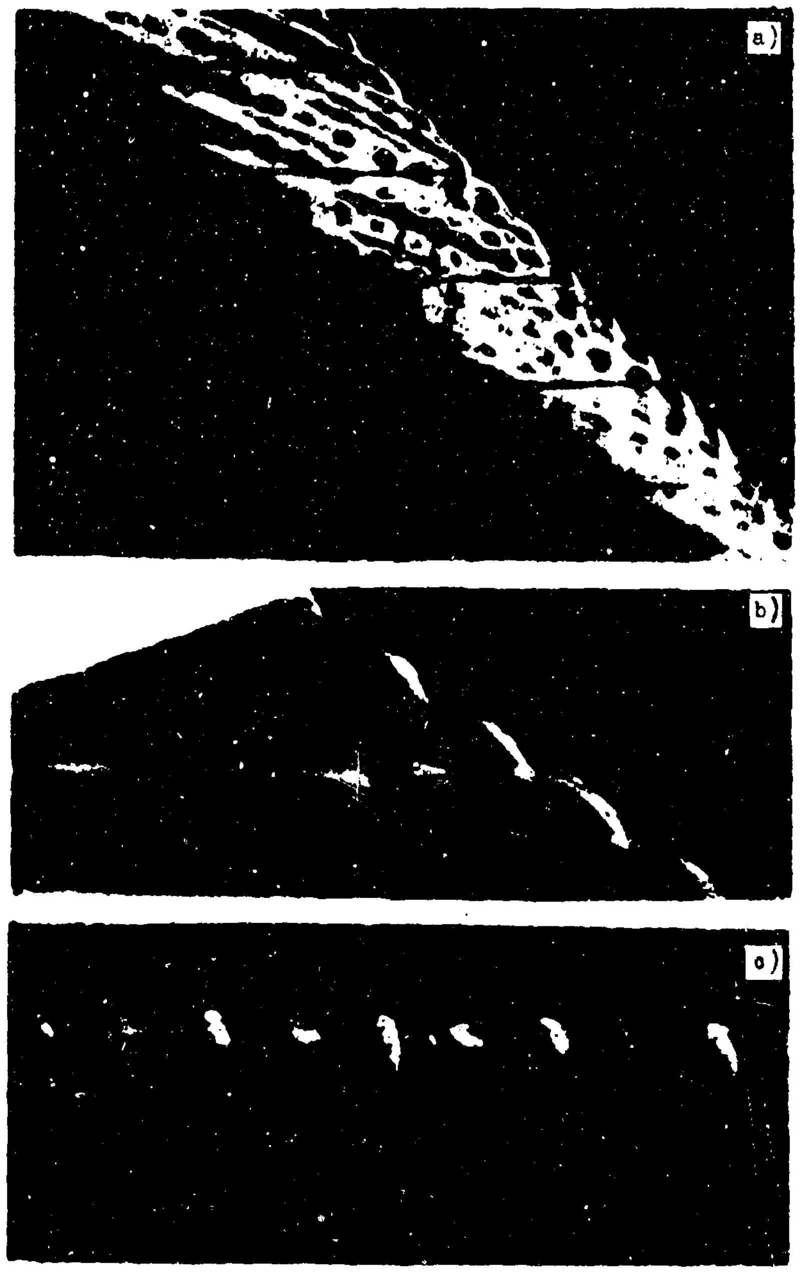


Fig. 15. Phototracings of self-luminosity.

that even with such a set-up of the experiment, with sufficient resolving power of the optical system it is possible to reveal the transverse wave. Photograph (c) was made with total compensation; on it, it is possible to see alternation of clear and unclear pictures. This is due to the fact that the head during every turn passes by the slot twice: once – along the near, and the other time – along the

wall of the tube farther from the slot. Motion at the near wall is compensated. At the far wall, transverse speed velocity is directed in the opposite direction; there is no compensation, and the photographs are obtained to be blurred.

Fig. 16. Photograph of self-luminosity by the method of total compensation with axial screen.

For removal of the unclear half-periods, into the tube there was inserted a narrow axial screen, which blocked the phenomenon on the distant wall (see Fig. 13). Inasmuch as the whole process is localized near the inner surface of the tube, such a screen did not affect spin. One of the tracings obtained in such a set-up is presented in Fig. 16.

The structure of the spin detonation wave is completely photographed on the moving film during one period of turn; further the photograph is repeated. The process of scanning can be represented in the following way. Let us fix the instantaneous position of the film and detonation and imagine that the detonation tube is a typographical rotator, on the surface of which there is applied paint in accordance with the distribution of luminosity. If we roll such a rotator over the film, there will be obtained a periodic imprint of the image.

For establishment of the position of shocks there was applied the method of Toepler. The necessity of such experiments was dictated by the fact that on the picture of self-luminosity the relatively weakly luminous shocks may be invisible. The difficulty of setting up the experiment in round tubes, which is due to the curvature of the surface, could be overcome in the following way. The external surface of the metallic detonation tube was cut along a plane in such a manner that in the wall there were formed narrow slots, which were covered with optical glass. In our experiments the diameter of the tube was equal to 27 mm; width of slot was 4 mm. Deviation of surface of tube from cylindrical was less than 0.2 mm.

Photography on the Toepler installation IAB-451 was produced by the method of total compensation. The axis of the detonation tube was set at an angle of arc tan 0.5 to the optical axis of the instrument, in such a manner that there was no superposition of contours of the leading front on phenomena occurring at the rear wall of the tube. Thus, it was possible to obtain a full picture of shocks in the region of the head, the photograph of which is shown in Fig. 18b. For comparison, on the same figure there is given a phototracing of self-luminosity a, obtained in the same set-up of the experiment.

Toepler photographs reveal that before the transverse wave there exists a front of preliminary compression, which has been revealed also by other methods [17, 18].

On the basis of the obtained results the picture of flow during spin detonation looks as follows: During propagation of the detonation wave in a gas, due to the large delay of ignition between shock wave and zone of combustion, there will be formed a region of gas, heated by the shock wave, in which chemical reaction has still not begun. Inside the heated zone, due to random causes, there can

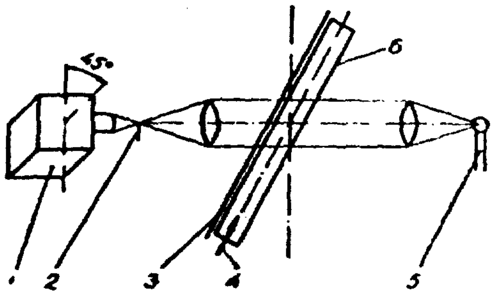


Fig. 17. Set-up of experiment in Toepler method with total compensation of speed. 1) photorecorder; 2) knife-edge; 3) screen with slot; 4) direction of detonation wave; 5) source of light; 6) detonation tube.

appear a disturbance which will lead to formation of a transverse detonation wave. Scattering of detonation products in the transverse wave causes perturbation of the leading front, which leads to formation of a discontinuity which is visible on the Toeplergrams (see Fig. 17) and which is revealed on prints of collision of the spin detonation front with the shock wave [21, 22, 23] (Fig. 18).

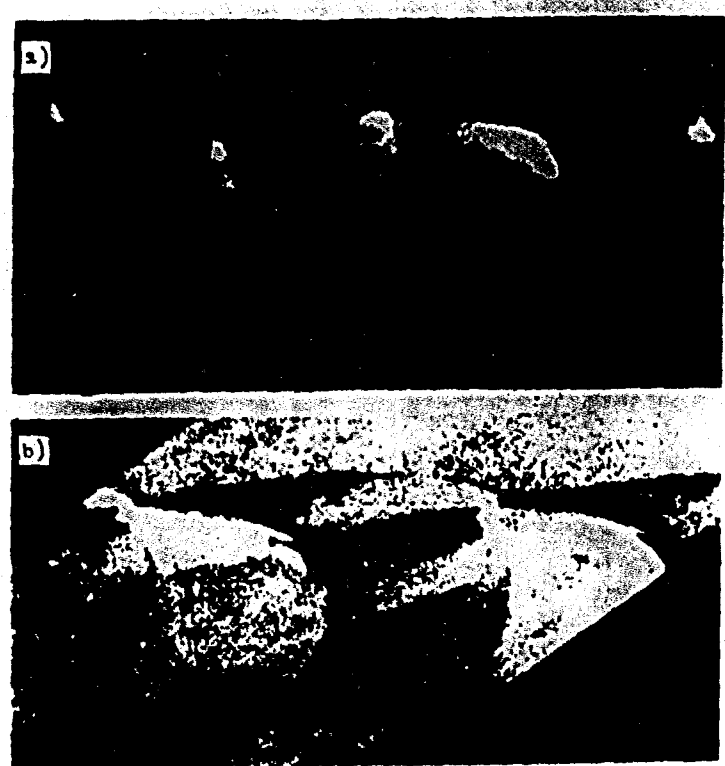


Fig. 18. a) photograph of self-luminosity in the set-up of Fig. 17; b) Toeplergram of spin.

Direction of rotation of transverse detonation wave is determined by random processes, but once it is determined it can no longer be

changed.

The scheme of flow in a system of coordinates connected with the transverse wave is seen in Fig. 19. In this system the gas flows in the detonation wave at an angle of about 45^o to the axis of the tube.

During passage through the shock wave, flow lines change their direction and are pressed toward the front. Calculations show (see § 4) that temperature of gas after the leading shock wave attains 1,000-1,100^{o}K. Speed of gas flowing into the transverse detonational wave is approximately 2,000 m/sec (for $2CO + O_2$). This means that the transverse detonation wave in this case is supercompressed.

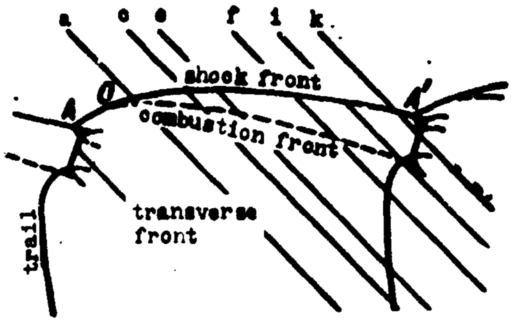


Fig. 19. Flow diagram for spin detonation. Scan of system of shocks on surface of tube.

With such a scheme of flow, even if the transverse detonation wave moved according to Jouget, pressure after the transverse wave would considerably exceed those pressures which could be observed in a scheme with a discontinuity, but without a transverse wave.

Indeed, if we assume that the discontinuity in the considered system of coordinates is perpendicular to flow lines (this will correspond to the highest possible speed of gas with respect to the shock, equal to $D\sqrt{2}$), then pressures which are developed after such a wave, even without taking into account chemical reaction, can attain a magnitude of not more than 65 p_0 for initial pressure p_0 and speed D = 1,750 m/sec. Pressures after the transverse wave have to attain magnitudes of more than 150 p_0, inasmuch as gas before transverse wave already is compressed to a pressure of the order of 20 p_0.

Exact calculations and detailed consideration of the scheme of flow will be given in § 4 of the given chapter.

§ 3. Measurements of Pressure Profile

From the above considerations the necessity of direct measurement of magnitudes of pressures, developed during spin detonation is understandable. Such measurements could also give information about character of phenomena developing in the trail of the spin detonation.

Mooradian and others [10, 11] were able to obtain a general picture of change of pressures during spin, but the method applied by them did not make it possible to measure magnitude of pressure in separate places of flow, inasmuch as the resolving power of the transducers was low: measurements were performed by transducer of tourmaline, which were placed in small cavities in wall of detonation tube connected by holes with active volume and filled with liquid. However, they were able to establish that in region after front there exist periodic oscillations of pressure, whose frequency coincides with frequency of rotation of spin; but it remained vague whether these changes have the character of jumps or occur smoothly.

Possibility of exact measurements of pressure was opened due to the creation of quick-response transducers of piezoceramics of barium titanate, whose sensitivity is two orders higher than that of tourmaline and quartz. The main investigations of such transducers and their development were conducted by S. G. Zaytsev [24]. At the same time, use of these transducers for the purpose of study of spin caused certain difficulties which were connected with small dimensions of flows observed during spin, and due to this with the necessity of obtaining high resolving power of the transducers. However, it was possible to surmount these difficulties:

In our experiments dimension of sensitive surface of transducer was reduced to 1 mm in diameter (Fig. 20) [25]. The transducer was

a cylindrical plate with height of 0.5 mm, soldered with Wood alloy to a long zinc rod.* (As was shown in work [24], zinc possesses the same acoustic resistance as barium titanate, and this leads to sharp decrease of reflection of pressure wave from the contact with the support.)

The rod with the transducer was placed on the axis of a protective brass tube with internal diameter of 6 mm. Remaining space was filled with beeswax heated up to a temperature slightly exceeding that necessary for its fusion. As one of the electrodes of the transducer there served the rod. The second face of the plate with help of a thin wire was connected with the brass tube. Filling with wax ensured good suppression of parasitic oscillations appearing during passage through of the pressure pulse.

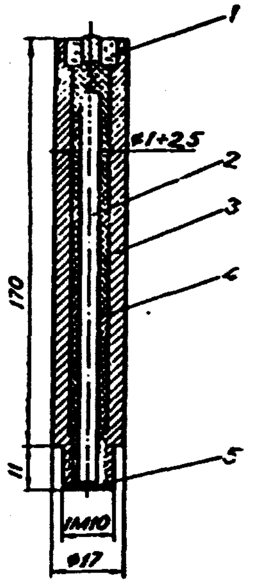


Fig. 20. Design of pressure transducer. 1) plexiglas bushing; 2) zinc rod; 3) housing (brass; 4) wax; 5) barium titanate plate.

Special attention was paid to overcoming acoustic pickup appearing in the detonation pipe during passage through of the detonation. Since speed of sound in metal considerably exceeds speed of detonation, then perturbations caused by explosion propogating through the pipe arrive earlier than the detonation wave and can distort the recording of pressure. For suppression of such pickup, the detonation tube was divided into 2-3 sections separated by rubber partitions. In the last section in the direction of

*Polarized plates are analogous to ferromagnetic materials in their properties and have a Curie point — the temperature at which polarization disappears. Together with destruction of polarization there is sharply lowered the sensitivity of the transducer. For barium titanate, the Curie point lies near a temperature of the order of 130°C; therefore, for soldering there was used solder with a composition close to that of Wood alloy, with melting point of 70°C.

motion of the wave there was installed the transducer, mounted in a plastic fitting. Application of such a device ensured practically full absence of acoustic pickup on the transducer (Fig. 21).

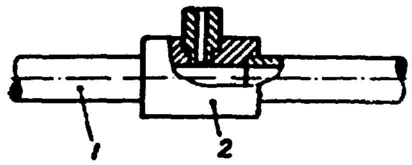


Fig. 21. Installation of transducer in detonation tube. 1) metal pipe; 2) plexiglas bushing.

Character of internal impedance of the transducer was purely capacitive. Magnitude of self-capacitance was about 100 pf; input impedance of amplifier was about 10 Mohm. In order to ensure absence of steep slope of the horizontal part of the signal, it is necessary to have a large time constant of the circuit consisting of transducer and input impedance of the amplifier. For this, in parallel with the transducer there was connected an additional capacitor of up to 10,000 pf. Under these conditions, a signal with duration of up to 10^{-2} sec is known to be recorded without frequency distortions. Time of recording of signal attained 400 μsec. Magnitude of input signal, due to high sensitivity of transducer, was much higher than the level of noises and pickup, in spite of its attenuation due to connection of the additional capacitor. Sensitivity of the plate constitutes a quantity of the order of 1 v/atm; lowering of the signal by 100 times with connection of the additional capacitor, with subsequent amplification by 1,000 times, ensured reliable recording at initial pressures in the region of 200 mm Hg.

For measurement of the entire pressure profile it was necessary to ensure recording of pressures during passage through the transducer of various sections of the front. For this ~~purpose~~, in the initial segment of the detonation tube there was installed a piece of spiral twisted from wire with thickness of about one and a half millimeters. Step of spiral was chosen close to the step of spin. As experiments showed,

such a device absolutely reliably gives the direction of rotation, and, due to constancy of the step of the spin, also the definite region of the front in which there was produced recording of pressure. By changing angle of rotation of the segment of pipe relative to the transducer, it was also possible to change position of the spin detonation front at the moment of passage through the sensing plate.

Recording was produced on a double-beam oscillograph OK-25 by a two-channel circuit immediately by two transducers located on opposite walls of the tube in one cross section. The front passed through transducers located at two diametrically opposite points. In Fig. 22 there is given the pressure recording by two such transducers.

Fig. 22. Recording of pressure during spin by two transducers located on opposite sides of the tube in the same cross section.

Consecutive photographing of spin for various angles of rotation of the section with the spiral gave a series of oscillograms, part of which are shown in Fig. 23; total time of scanning is of the order of 400 μsec. Attentive consideration of the given oscillograms reveals gradual transition from one form of pressure profile to another. Reproducibility was so good that often it was impossible to distinguish photoprints of oscillograms of different experiments conducted under identical conditions from each other.

On the given oscillograms there are obvious oscillations of pressure caused by passage of the trail. It is possible to see that character of oscillograms corresponds to the diagram of flow shown in Fig. 19. For understanding of the entire picture of flow, it was necessary to conduct correlation of pressure profile with the system of shocks. For this, on the diagram there were plotted trajectories

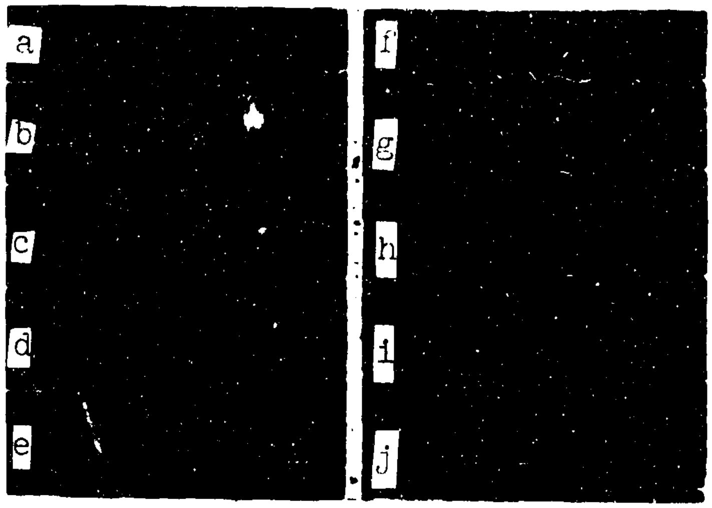


Fig. 23. Oscillograms of pressure during spin for various angles of turn of igniting section of pipe. Mixture $2CO + O_2$, saturated with water vapor at 20°C; time of scan is ≈400 μsec. Letters designate oscillogram is corresponding to trajectories of transducers in Fig. 19.

of the pressure transducers. Inasmuch as the transverse wave moves along a spiral with an angle of about 45° to the generator, then in the system of coordinates connected with it the transducer passes through the picture of flow at the same angle. Thus, trajectories of transducer on a given diagram in various experiments are straight lines, inclined to axis of the tube at the indicated angle. Plotting of the trajectory corresponding to the given oscillogram was produced by combination in the same scale of time of any two characteristic points of the oscillogram with two analogous points on the diagram of fronts. For instance, for oscillogram j such points were the transverse front and direct shock wave. Check of selected position of trajectory was carried out according to oscillograms of the second transducer. The latter were plotted on the picture of flow automatically shifted by a half of a period. Coincidence of shocks on oscillogram of second transducer with shocks of the diagram of flow

dicated the correctness of tracing of the trajectory.

Let us consider the oscillogram in greater detail. During trans-ion from oscillogram a to j it is possible to see that peak of essure corresponding to the leading shock front AOA' (see Fig. _) adually decreases in magnitude. The second rise following after is peak, conversely, increases, simultaneously moving forward along e oscillogram. On the diagram of shocks this corresponds to dis-acement of the trajectory of the transducer along the front from to A'. With such displacement, due to increase of angle of flow th the normal to the front, pressure in the first shock should drop. e second rise, conversely, is strongly increased, inasmuch as ajectories intersect the trail at points, closer and closer to the ont of the transverse detonation wave. As a result, on oscillogram which establishes passage through the transducer of the transverse tonation wave, in the second peak there is recorded a pressure proximately 8 times greater than the preliminary compression shock.

For more detailed investigation of the field of pressures in the ighborhood of the leading front there were conducted experiments h increased speeds of scanning. In this case pressure was recorded multaneously by four transducers on two oscillographs OK-17M.

Transducers were calibrated directly in the detonation tube by a ck wave from the explosion of a suspension of hexogene. There were orded the direct wave and the wave reflected from the end of the e, near which the transducer was located. Calculation of magnitude pressure was produced according to speed of shock wave, which was sured with help of other transducers. Calibration curve is shown Fig. 24.

For establishment of position of trajectory of transducers ative to the detonational wave in these experiments, simultaneously

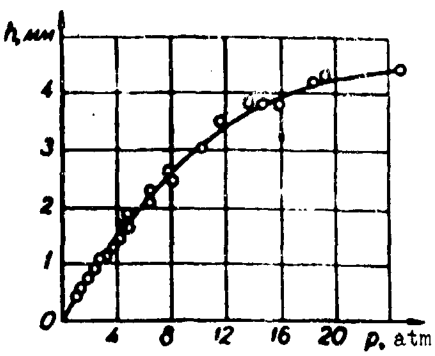


Fig. 24. Calibration curve.

with [illegible] there was [illegible] photo-recording of self-luminosity by the method of total compensation. Relative location of slot and transducers on wall of detonation tube is shown in Fig. 25. The slot was covered with thin opaque strips along the line of motion of the transverse wave drawn from the transducer. On the phototracings in this case there remain dark lines, corresponding to trajectories of the transducers (Fig. 26).

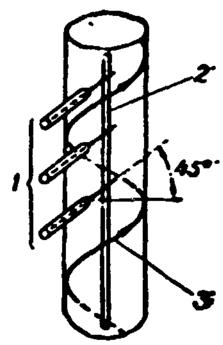


Fig. 25. Setup of experiment on measurement of pressure with simultaneous photo-recording. 1) transducers; 2) slot; 3) direction of motion of head of spin.

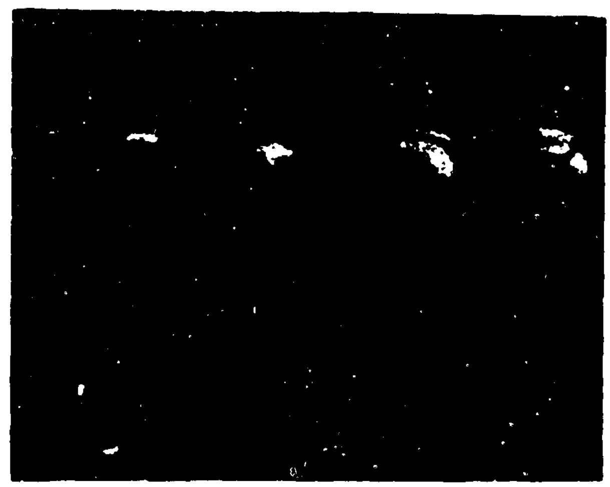


Fig. 26. Phototracing of spin with traces of trajectories of the transducers.

In Fig. 27 there are given oscillograms of pressure in region of the leading front together with the diagram of flow with corresponding trajectories of transducers plotted on it. Distance between vertical lines on oscillograms is equal to 5 μsec; between horizontal lines — 25 units of initial pressure of the mixture. Lines are plotted according to calibration curves, taking into account nonlinearity of the oscillograph. The qualitative picture of flow here is the same as with slow scanning.

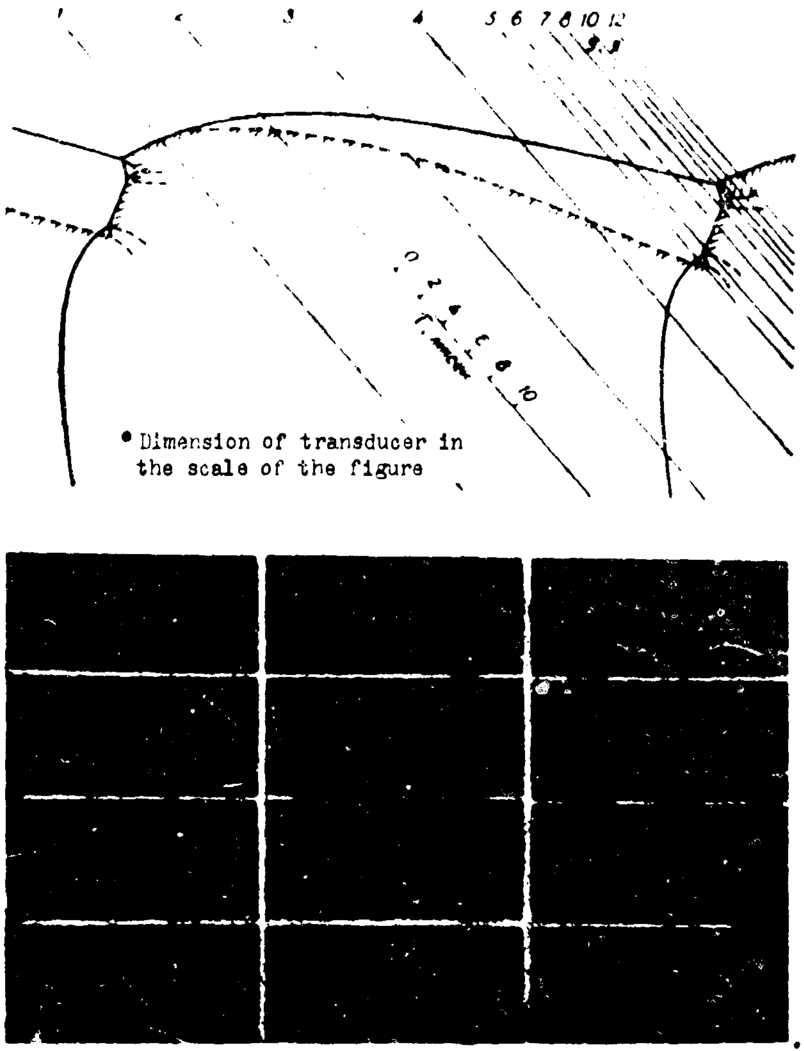


Fig. 27. Oscillograms of pressure during spin and their relation to the system of shocks.

Special attention here should be paid to oscillograms 8, 9, 10. On oscillogram 8, before the peak of pressure at 160 p_0, there is registered a preliminary rise of approximately 19 p_0, which corresponds to the passage of the leading front. Oscillogram 9 registers passage of the transducer in direct proximity to the triple point corresponding to the tip observed on the phototracings. The character of change of pressure attracts attention: a jump up to approximately 45 p_0, an almost continuous rise to 63 p_0, a short plateau' and then a jump to 160 p_0. We give an explanation to this phenomenon in the following paragraph. For oscillograms 10 and 11 there is characteristic an initial jump to a pressure of approximately 50 p_0, and then

a continuous growth in case 1 up to approximately 12[illegible] p_0, and in case 11 — up to 1[illegible]0 p_0, where in case 10 we may see formation of a plateau with duration of approximately 2 μsec.

During the analysis of photographs from 7 to 2, we may see how the transverse wave, decreasing pressure, goes back along the oscillogram, gradually losing its discontinuous character and degenerating into a wave of finite amplitude ($p \approx 50\ p_0$ on line 3) without a discontinuity. By the earlier given photographs with long scanning (see Fig. 23), it is possible to see that it will be transformed into a trail.

Thus, measurements with the help of pressure transducers has completely confirmed the picture of fronts obtained by optical methods.

§ 4. Analysis of Scheme of Flow with Transverse Wave

Calculations show [17, 18, 19, 20] that with the help of one triple point it is not possible to coordinate flow after the transverse detonation wave and discontinuity of the leading front.

Consideration of photographs of self-lumunosity and Toeplergrams of the process showed that in the region of interaction of the leading front with the transverse detonation wave there are revealed two triple points. Therefore, there was constructed [26] the diagram of flow presented in Fig. 28. Here A_1AA_2 is the front of the leading wave; AB is the shock wave which compresses the gas to the pressure after shock AA; BD is the shock wave which compresses the gas of region 3 to the pressure after transverse wave BC. Coordination flow of regions 4 and 2 occurs in the centered rarefaction wave which occupies region KDF, if flow in region 4 is supersonic; otherwise, such coordination is impossible.

We will consider that all shocks approach the wall perpendicularly; then flow near lines of their intersection with the wall will

be two-dimensional.

As initial data for calculation there were taken speed of detonation, initial parameters of the mixture p_0, ρ_0, T_0 and angle of wave AA_2 with the flow, which was determined by Toeplergrams. Calculation was carried out for the mixture $2CO + O_2$ at $p_0 = 0.1$ atm, $T_0 = 293^\circ$ K, D = 1,700 m/sec. First of all, under the assumption of absence of reaction, there were determined all parameters of the gas after shock wave A_1AA_2.

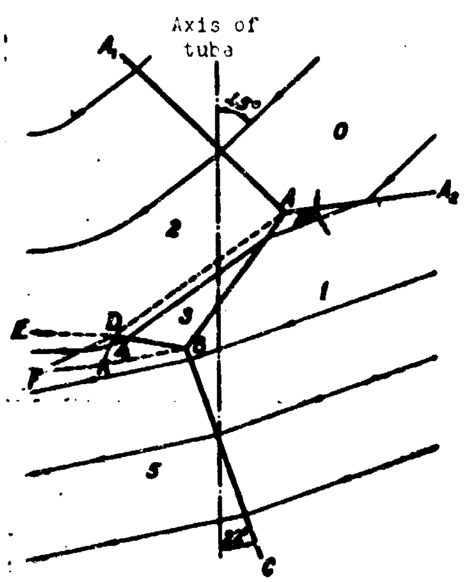


Fig. 28. Diagram of shocks in the region of upper triple points. 1) shocks; 2) contact discontinuities; 3) removable discontinuities (first and last characteristics of rarefaction wave).

Pressure drop across oblique shock wave is determined by relationship

$$p_1 - p_0 = \rho_0 u_0^2 \sin^2 \varphi \left(1 - \frac{\rho_0}{\rho_1}\right). \qquad (2.1)$$

Here p, ρ, u, φ are pressure, density, total velocity and angle of incident flow with front; subscripts 0 and 1 pertain to states before and behind the shock wave front. Equation of shock adiabat

$$\Delta I = \frac{p_1 - p_0}{2}\left(\frac{1}{\rho_0} + \frac{1}{\rho_1}\right). \qquad (2.2)$$

Let us add here equation of state of ideal gas

$$p = \rho \frac{RT}{\mu} \qquad (2.3)$$

and the relation between specific enthalpy I and temperature

$$\Delta I = f(T). \qquad (2.4)$$

Let us introduce dimensionless variables

$$\pi = \frac{p_1}{p_0} \text{ and } \sigma = \frac{\rho_1}{\rho_0}.$$

Then equations (2.1)-(2.4) will be transformed to the form

$$\pi - 1 = \frac{\rho_0}{p_0} u_0^2 \sin^2 \varphi \left(1 - \frac{1}{\sigma}\right); \tag{2.5}$$

$$\Delta I = \frac{\pi - 1}{\frac{2p_0}{\rho_0}} \left(1 + \frac{1}{\sigma}\right); \tag{2.6}$$

$$\pi = \sigma \frac{T_1}{T_0}; \tag{2.7}$$

$$\Delta I = f(T). \tag{2.8}$$

The last system of equations is easy to transform to a form convenient for calculations. Let us introduce parameters determined by the initial conditions:

$$A = \frac{\rho_0 u_0^2}{p_0} \sin^2 \varphi \text{ and } B = \frac{2p_0}{\rho_0}.$$

Then, by eliminating from (2.5) and (2.6) quantity σ, we obtain a relation for ΔI expressed only in terms of π:

$$\Delta I = \frac{\pi - 1}{B} \left(2 - \frac{\pi - 1}{A}\right). \tag{2.9}$$

The value of T can be found from the tables for known value of ΔI. Further we have

$$\sigma = \frac{\pi T_0}{T_1}, \tag{2.10}$$

$$\pi = A\left(1 - \frac{1}{\sigma}\right) + 1. \tag{2.11}$$

Solution of equations (2.9)-(2.11) was conducted by the method of successive approximations. By values of p_1, ρ_1, T_1 determined from calculations it is possible to calculate all interesting parameters of the gas: tangent of angle of flow relative to the front behind the shock

$$\operatorname{tg} \psi = \frac{\operatorname{tg} \varphi}{\sigma}, \tag{2.12}$$

the angle through which velocity vector of the flow turns

$$\omega = \varphi - \psi. \tag{2.13}$$

total flow velocity

$$u_1 = \frac{u_0 \cos\varphi}{\cos\psi}, \tag{2.14}$$

speed of sound

$$c_1 = \sqrt{\frac{\gamma_1 p_1}{\rho_1}} \tag{2.15}$$

(γ_1) is determined by T_1 with help of tables); and, finally, Mach number

$$M_1 = \frac{u_1}{c_1}. \tag{2.16}$$

Results of calculations of flow behind the leading shock wave are shown in Fig. 29, from which it is possible to see variation of parameters of gas along front of leading wave. Along the axis of ordinates there are plotted dimensionless quantities π, σ, M, and also temperature T and angle of turn of flow ω. Along the axis of abscissa there is plotted angle of incident flow φ and quantity u_{n0}^2 — square of normal component of flow velocity.

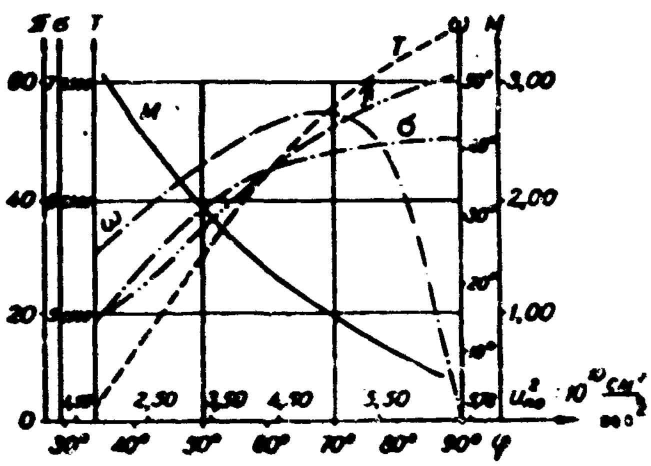


Fig. 29. Parameters of gas behind the front of the leading wave.

With shift along the leading front from A to A' (see Fig. 19), temperature T_1 monotonically decreases. Accordingly there are increased delays of ignition. Due to this, at a certain point O, the combustion front starts to sharply lag behind. This one may see well during comparison of photographs of self-luminosity and Toeplergrams (see Fig. 18).

Thus, it is possible to consider that length of front AA' is a detonation wave between points A and O. After separation of the combustion zone, the detonation wave becomes a shock wave, practically without noticeable chemical reaction. The layer of gas remaining behind

the shock wave OA' is almost wholly burned in the transverse front. Only a small part of it passes through the combustion front OG.

We will consider now flow in the region of the triple point A (see Fig. 28). From this point there depart three shocks (A_1A, AA_2 and AB) and contact discontinuity AD. Gas passes through system of discontinuities as is shown in the figure. According to experimental measurements, angle of inclination of trajectory of head for mixture $2\ CO + O_2 + 3\%\ H_2$ is equal to $44^\circ\ 13'$. Angle of flow with shock AA_2 is determined to be equal to $35^\circ\ 34'$ from the Toeplergrams. For flow velocity $u_0 = D/\cos 44^\circ\ 13'$ (D = 1,700 m/sec), angle of outgoing flow is $8^\circ\ 15'$. Thus, the flow turns through an angle ω equal to 27° 19'.

For construction of the flow, it is necessary to satisfy the condition of equality of pressures on both sides of the contact discontinuity AD and the condition of identical directions of velocities. Preliminary calculation was conducted for the case when shocks are shock waves without chemical reaction. Finding of the solution was conducted by the graphic method according to shock polars in plane (π, ω).* For this there were constructed curves of pressure behind the shocks as a function of angle of turn of the flow. Such a construction was carried out for shock A_1A, into which there flows gas with initial state, and for shock AB, the state before which is determined in the above calculations.

The obtained dependences were constructed on one graph (Fig. [illegible]). As the reference line for the measurement of angles there is selected the direction of flow in region [illegible]. Turn of the flow on shock AA_2 will be considered to be positive. Inasmuch as the flow in region 1 will turn relative to its initial direction, the polar for it is constructed

* This method of calculation of triple configurations was used by Ya. K. Troshin and colleagues [21-2[illegible]].

as shifted by the corresponding angle to the right. Points of intersection of polar 1 with polar 0 determine two possible configurations, shown in Fig. 31a and b. Comparison with Toeplergrams shows that there is realized a regime corresponding to Fig. 31a.

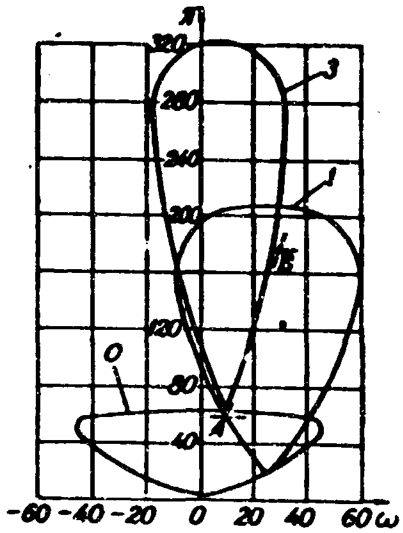


Fig. 30. Construction of solution by detonation polars.

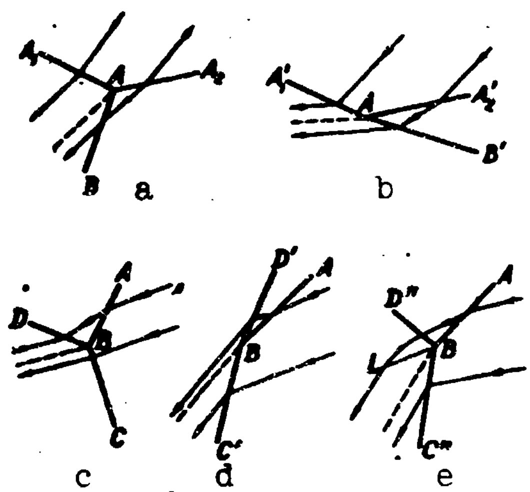


Fig. 31. Possible configurations of shocks near triple points A and B.

Analogous calculations were conducted for triple point B. Here as the initial state there was taken the state of gas in regions 1 and 3. For the selected configuration at point A, the flow in region 3 will turn relative to the initial state by a smaller angle than in region 1; this corresponds to shift of polar 3 to the left.

As in the first case, here there are possible the two positions of shocks depicted in Fig. 31c and d. In case d front BD' turns out to be inclined downstream. Calculation shows that the flow behind shocks BD and BD' is supersonic; consequently, disturbances can propagate along front BD' only from point D' to point B. In the considered case, in the flow there are absent causes which can generate such disturbances at point D'. Furthermore, in this variant, the slope of front BC' considerably differs from that measured experimentally. For these reasons, at point B there was selected a

configuration of type c.

Calculation showed (see Fig. 28) that temperature in regions 2 and 5 exceeds 2,600°K. Behind front AB in region 3 the temperature is less than 1,500°, and in region 4 – less than 2,000°. On phototracings of self-luminosity, bright regions 2 and 5 are separated by a dark band, which corresponds to regions 3 and 4. For these reasons, in the final variant fronts AA_1 and BC were considered to be detonation fronts with instantaneous chemical reaction to the equilibrium state, and jump AB was considered to be a shock. In spite of the high temperature behind shock BD, the latter also was taken to be a shock without chemical reaction.

If we consider that front BD is a detonation wave (flow velocity in region 3 somewhat exceeds Chapman-Jouget speed of detonation in this region, which is equal by calculation to 1,670 m/sec), then pressure, developed behind it will exceed the pressure behind the transverse wave. Angle of wave BD" with flow will be established such that expansion of products behind it in rarefaction wave will lead to a sharp turn of the contact discontinuity downwards and corresponding turn of front BC" (see Fig. 31e) by angles sharply differing from experimental. Furthermore, with consideration of the finite width of the zone of chemical reaction after the detonation shock BD", a stationary configuration of type Fig. 31e at point B is totally impossible. In Fig. 30, the position of the triple configurations with detonation shocks AA_1 and BC is shown by dashed lines.

Supersonic flow velocity after shock BD (see Fig. 28) makes it possible to coordinate flow on contact discontinuity DE with the help of centered rarefaction wave. During calculation of zone KDF it was considered that ratio of heat capacities of the gas remains constants. The position of the first characteristic of the

rarefaction wave and the region occupied by it was determined by usual formulas (see, for instance, [27]).

It is necessary to note the following: During calculation, all fronts were assumed to be rectilinear and pressure in regions 1-4 was assumed to be constant. In reality pressure along contact discontinuity AD in the plane case should increase, attaining at point D the total stagnation pressure flow 2. This will lead to distortion of the contact discontinuity AD; flow in regions 2, 3 and 4 will become nonuniform, and consequently shocks AB and BD will not be straight lines. However, in view of the comparatively low flow velocity in zone 2, changes of pressure along AD are small, and in the first approximation it is possible to disregard distortions.

The first characteristic of the rarefaction wave KDF emerges onto the contact discontinuity BKF at some point K. Continuation of it into the region of subsonic flow 5 is impossible. For stationarity, it is necessary that by the moment of emergence of the first characteristic of the rarefaction wave onto contact discontinuity BKF, the speed of gas in region 5 become supersonic. Otherwise, the rarefaction wave will overtake front BC.

In the plane scheme, flow in region 5 is subsonic divergent; therefore, its velocity and Mach number must drop, and pressure must increase. However, judging by the oscillograms, there occurs a sharp drop of pressure directly after shock BC. Consequently, in reality, flow velocity increases. This is possible to explain only by the fact that after the transverse detonation wave, flow lines are pressed to the wall (cross section of flow tubes near the wall decreases). At the point where there occurs transition of flow through the speed of sound, pressure is equal to critical. As calculations show, critical

pressure in region 5 is equal to 115 p_0.

According to oscillograms of pressure, it is possible to establish the time in which pressure drops to its critical magnitude and, consequently, the distance of the sonic line from the front. For flow lines passing near point B, this distance with accuracy up to errors of measurement and calculations corresponds to the length of segment BK.

We will note also that in a very small neighborhood of triple points it is necessary, of course, to consider that chemical reaction after shocks AA_1 and BC have still not been complete. However, it is possible to imagine a neighborhood of the triple points such that reaction after shocks AA_1 and BC has already passed, and after AB and BD has still not started due to the fact that temperatures, and consequently delay times, are different. Our calculation was produced for just such a neighborhood of triple points.

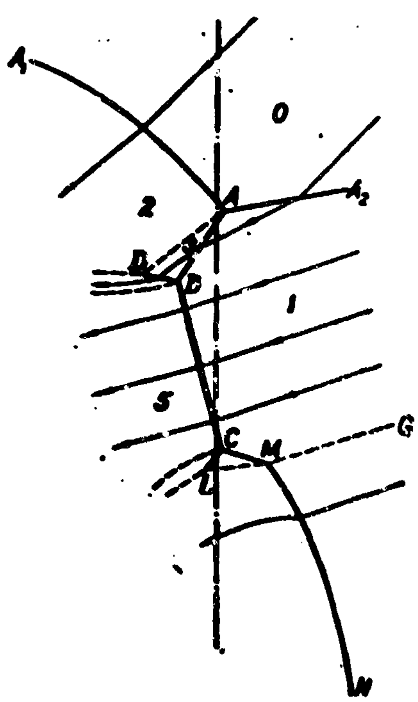


Fig. 32. Diagram of flow in region of transverse wave.

Consideration of Toeplergrams and photographs of self-luminosity of the process (see Fig. 16 and 18) gives us cause to assume (Fig. 32) that flow after the lower end of the transverse detonation wave and the adjacent part of trail MN are coordinated with the help of triple points C and M, which are analogous to points A and B. Near point M the trail is a shock wave with a clearly expressed front. With distance from point M the trail gradually degenerates into an acoustic wave of finite amplitude (see below § 3).

In Fig. 33 there is given a photograph of the trace of a spin detonation on the sooty wall of the tube. The trace of motion of the head here is a wide band bounded by two pairs of thin lines, which obviously correspond to triple points A, B, C and M.

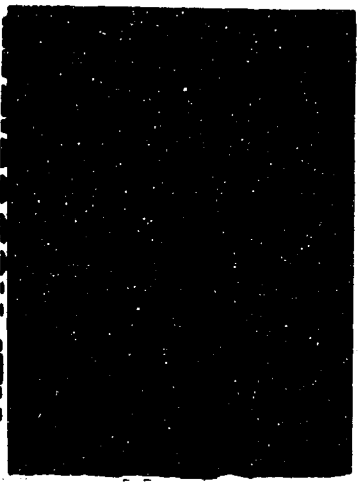


Fig. 33. Trace of transverse wave on sooty wall of detonation tube.

Calculation of flow near triple points C and M was not carried out, inasmuch as parameters of the incident flow on both sides of the combustion front MG are unknown.

The transverse wave front, as already was indicated, is supercompressed. Chapman-Jouget speed of detonation with respect to state 1 is close to 1,720 m/sec, whereas in reality the speed of the transverse front with respect to the gas turns out to be equal to 1,950 m/sec, i.e., there occurs supercompression with respect to pressure of approximately 2 times. It is known that such a detonational front, in general, cannot propagate independently with constant speed.

Causes of stability of the transverse front are revealed during the examination of impressions due to collision of the spin detonation wave with the end of the tube. As the photograph, in Fig. 34 shows,* in the volume of the tube there are developed configurations consisting of incident 1 and reflected 2 waves. The irregular reflection

*R. E. Duff [28] published a photograph of the impression on the end of the tube which noticeably differed in shape from that obtained by us. Length of "leg" 3 in his photo is relatively shorter, and "whiskers" 1 and 2 are longer. During multiple repetition of such experiments with mixtures of $2H_2 + O_2$ and $2CO + O_2$ + (2 to 7%) H_2 in glass tubes with diameter form 20 to 40 mm, we came to the conclusion that during stable spin detonation, the impressions take a form similiar to Fig. 34, and impressions corresponding to those given in work [28] are observed only during non-steady-state spin.

appearing then leads to formation of a Mach leg 3, which is a transverse detonation wave. The extent of this wave along radius of tube is approximately 3/5 R. It is obvious that speed, corresponding to that calculated according to the Chapman-Jouget condition is attained at some intermediate point of the wave. This occurs at a point located at a distance from the wall of about 1/6 R.

Fig. 34. Photograph of impression of spin detonation on the end of the tube.

The accuracy of the proposed diagram of shocks (see Fig. 28) is confirmed by all avialable experimental material. Shocks AA_1, AA_2, BC, triple points A and B, zone of low temperature after jump AB and the analogous zone in the region of lower triple points are revealed on photographs of self-luminosity and Toeplergrams. Angle of front BC calculated according to the given diagram coincides with that which was experimentally measured with accuracy up to 1 degree. Only the angle of inclination of front AA_1 noticeably differs from the calculated value. Measurement of profile of pressures confirmed the existence of a shock of preliminary compression AA_2 and of a zone of very high pressure 5. Oscillogram 9 in Fig. 27 reveals front BD, which due to its small dimensions is not registered by optical methods. Continuous rise of pressure from 45 to $63 p_0$ is explained by the fact that the transducer partially passed through region 1.

Comparison of measured values of pressure with calculated values shows the good coincidence of the neighborhood of triple points A and B, although behind front BC measured pressures are somewhat lower. This disagreement can be explained by the presence of 3% hydrogen in the mixture $2CO + O_2$ applied for measurement of pressures, which was not considered during calculation of the state behind fronts AA_1 and

BC, and also by the fact that at distances of the order of AB, flow can no longer be considered to be two-dimensional. In Table 2 there are given parameters of the gas in the region of triple points during spin detonation for the scheme shown in Fig. 28 (mixture $2CO + O_2$, $D = 1{,}700$ m/sec, $p_0 = 0.1$ kg/cm^2, $T_0 = 293^\circ$K).

Table 2.

Shock	Pressure behind shock, relative to p_0: Theory	Pressure behind shock, relative to p_0: Experiment	Temperature behind the shock degrees K	Density after the shock with respect to ρ	Total flow velocity after shock* m/sec	Mach number after shock	Angle of shock with generatrix of tube: Theory	Angle of shock with generatrix of tube: Experiment	Angle of flow with front before the shock	Angle of flow with front after the shock
AA_{1sh}	60,8	—	2660	—	—	—	—	—	—	—
AA_{1det}	54,5	52±5	3550	4,88	491	0,446	48°47′	60°±10°	87°	75°40′
AA_2	19,25	19±1	1140	4,92	1950	2,97	—	79°47′	35°34′ (эксп.)	8°15′
AB	54,5	—	1500	10,48	1720	2,31	39°	—	32°32′	15°50′
BD	170	160±10	2020	23,76	1290	1,5	86°30′	—	47°30′	28°55′
BC_{sh}	195	—	2610	—	—	—	—	—	—	—
BC_{det}	170	155±10	3730	14,48	663	0,616	21°15′	21°±2°	87°	84°

*In system of coordinates connected with the shocks.

Decrease of pressure drop along front BC during transition to lower flow lines, which was revealed by the transducers, is due to the fact that temperature of gas flowing from region 1 into lower sections of the transverse front is higher than it is near point B, since the corresponding particles of gas pass through the front of the leading wave at points of higher pressure drop. The subsequent adiabatic expansion of these particles to a pressure near point B cannot lead to total temperature balance before the transverse wave.

Maximum measured pressures in transverse wave attain 160 p_0.

In the schemes of flow without transverse detonation wave, proposed earlier by other authors, [13-14], the highest pressures, as we already said, cannot in any variants considerably exceed 65 p_0. These schemes of flow are refuted also by the photographs of self-luminosity and Toeplergrams given here.

§ 5. Acoustic Theory

One of the most remarkable properties of spin — the exceptional constancy of the step of the spiral described by the transverse wave — actually is not explained by consideration of the picture of flow in the region of the leading front. Change of frequency of rotation of spin upon the introduction of concentric inserts suggests a possible influence of purely acoustic processes on spin. Inasmuch as the fronts are localized near the walls, such inserts cannot affect the front, but strongly change acoustic characteristics of the volume of gas behind the front.

During the study of phenomena on the front, it is not possible to explain formation of the trail of the spin detonation which was observed by Campbell. During examining of photoscans on photographs, there is revealed a system of bands of almost vertical direction (see Fig. 15a), which appears during repeated passage of the trail past the slot. The nature of the actual trail has remained vague. Assumptions that the trail is formed by a rotating heated column of gas conflict with the law of conservation of momentum, and, therefore, cannot be correct.

The observed phenomenon should be connected with increase of temperature, inasmuch as there is sharply increased luminosity of the gas. Due to the fact that this phenomenon cannot be a rotating gas column, it remains to assume that in this case there occurs rotation

of the region of elevated pressure which appears due to oscillations of the gas.

Such an explanation of the phenomenon was given for the first time by N. Manson. Assuming that oscillations occur at natural frequencies of the volume of gas behind the front, Manson obtained exceptional agreement between experimentally measured and calculated frequencies of rotation of the spin [29, 30]. However, in spite of this, up to the appearance of works of Fay [31], who proposed an analogous theory in 1952, the works of Manson were little known.

In his calculations Manson did not consider the possibility of occurrence of oscillations along the axis of the tube and considered them to be completely transverse. Fay made an attempt to construct a three-dimensional theory, but his reasonings concerning boundary conditions along z are inaccurate. Actually he could not correctly formulate the boundary condition on the detonation front [31].

The fact of the possibility of application of the linear wave equation to a problem which is nonlinear in essence is itself questionable; however, within the limits of the problem of determination of frequencies, in spite of all its inaccuracies the theory gave exceptional agreement with experimental material. This awakened interest in such an approach to the solution of the problem of spin.

Let us consider the problem in Manson's approximation. Let us be limited to consideration of the two-dimensional wave equation for velocity potential of a gas in cylindrical coordinates:

$$\frac{\partial^2 \varphi}{\partial r^2} + \frac{1}{r}\frac{\partial \varphi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \varphi}{\partial \theta^2} = \frac{1}{c^2}\frac{\partial^2 \varphi}{\partial t^2}. \tag{2.17}$$

Here φ — velocity potential of particles of gas;

c — speed of sound in gas behind detonation wave front;

r and θ — polar system of coordinates connected with the gas, the pole of which is on the axis of the pipe.

Boundary conditions:

1. $$\left.\frac{\partial\psi}{\partial r}\right|_{r=R_0}=0; \tag{2.18}$$

2. $$\psi(r, \theta, t)|_{r=0}<A \quad \text{(bounded)}; \tag{2.19}$$

3. $$\psi(r, \theta, t)=\psi(r, \theta+2\pi, t)- \tag{2.20}$$

is periodicity with respect to θ. R_0 is radius of the tube.

We seek the solution of equation (2.17) in the form of the product

$$\Psi=\Phi(\theta)R(r)T(t). \tag{2.21}$$

Substitution into (2.17) gives

$$\frac{R''}{R}+\frac{1}{r}\frac{R'}{R}+\frac{1}{r^2}\frac{\Phi''}{\Phi}=\frac{1}{c^2}\frac{T''}{T} \tag{2.22}$$

(derivatives with respect to the corresponding variables).

Inasmuch as the right side does not depend on coordinates and the left side does not depend on time, we have

$$\frac{R''}{R}+\frac{1}{r}\frac{R'}{R}+\frac{1}{r^2}\frac{\Phi''}{\Phi}=\frac{1}{c^2}\frac{T''}{T}=-\lambda^2, \tag{2.23}$$

where λ^2 = const.

Variables are separated, and equation (2.23) is broken up into two:

$$T''+\lambda^2c^2T=0 \tag{2.24}$$

and

$$\frac{R''}{R}+\frac{1}{r}\frac{R'}{R}+\frac{1}{r^2}\frac{\Phi''}{\Phi}=-\lambda^2. \tag{2.25}$$

In equation (2.25) variables are also separated:

$$r^2\frac{R''}{R}+r\frac{R'}{R}+\lambda^2r^2=-\frac{\Phi''}{\Phi}=n^2. \tag{2.26}$$

We distinguish two equations:

$$r^2 \frac{R''}{R} + \frac{rR'}{R} + \lambda^2 r^2 - n^2 = 0 \tag{2.27}$$

and

$$\Phi'' + n^2 \Phi = 0. \tag{2.28}$$

General solution of equation (2.28) has the form:

$$\Phi = c_1' e^{p_1 \theta} + c_2' e^{p_2 \theta}. \tag{2.29}$$

Here p_1 and p_2 are roots of the characteristic equation

$$p^2 + n^2 = 0, \tag{2.30}$$

where n is a real number.

From (2.30) it follows that

$$p_1 = in,\ p_2 = -in, \tag{2.31}$$

therefore solution (2.29) has the form

$$\Phi = c_1 \sin n\theta + c_2 \cos n\theta. \tag{2.32}$$

The conditon of periodicity (2.20) can be satisfied only if n is an integer.

Equation (2.27) by replacemnt of $\lambda r = y$ is reduced to Bessel's equation

$$y^2 R'' + yR' + (y^2 - n^2) R = 0. \tag{2.33}$$

General solution of this equation for whole n is obtained in the form

$$R = c_3 J_n(\lambda r) + c_4 Y_n(\lambda r). \tag{2.34}$$

where J_n – Bessel function of 1-st kind and n-th order;

Y_n – Bessel function of 2-nd kind and n-th order.

From the boundedness of φ as $r \to 0$ it follows that $c_4 = 0$.

From condition (2.18) we obtain

$$J_n(\lambda_{kn} R_0) = 0. \tag{2.35}$$

i.e., quantities $\lambda_{kn}R_0$ are roots of equation (2.35), where λ_{kn} – K-th value of λ_n, satisfying equation (2.35).

General solution of equation (2.24) has the form

$$T = c_5 \sin \lambda_{kn} ct + c_6 \cos \lambda_{kn} ct. \tag{2.36}$$

Thus, the complete solution of the equation for potential is written as

$$\Phi = \psi_0 \sum_n \sum_k J_n(\lambda_{kn} r)\,[c' \cos(n\theta + \lambda_{kn} ct + \varphi_1) + \\ + c'' \cos(n\theta - \lambda_{kn} ct - \varphi_2)]. \tag{2.37}$$

where ψ_0, φ_1, φ_2, c' and c'' are constants.

Characteristic numbers n and k indicate respectively the number of waves, contained with change of θ by 2π and of r from 0 to R_0.

Thus, the solution of equation for velocity potential for given n and k describes two waves rotating in opposite directions with angular velocity $\lambda_{kn}c$; n determines number of antinodes of pressure on periphery of pipe in one cross section; k determine number of antinodes of pressure during motion away from center of pipe along the radius.

Angular velocity of rotation of each of waves contained in formula (2.37) can be obtained by differentiation of the argument of the cosine with respect to time:

$$\frac{d\theta}{dt} = \frac{\lambda_{kn} c}{n}. \tag{2.38}$$

Linear velocity of motion of wave on the wall

$$v = \frac{R_0 \lambda_{kn} c}{n}. \tag{2.39}$$

If it is considered that transverse disturbance in detonation front rotates with the same frequency as the antinode of acoustic oscillation behind the front, then angle of inclination of spiral described by the head to the axis of the tubes will be determined from relationship

$$\operatorname{tg}\alpha = \frac{v}{D} = \frac{R_0 \lambda_{kn}}{n} \cdot \frac{c}{D}. \qquad (2.40)$$

For one-headed spin detonation, there is one singularity along the radius and one along the circumference of the pipe. This corresponds to the case $n = K = 1$. Then $\lambda_{kn} R_0 = \lambda_{11} R_0 = 1.84$.

As we saw in Chapter I, the value of speed of sound behind the detonation front is not unique; for the mixture $2CO + O_2$ it is equal to

$$c_e = 0{,}542\,D \text{ and } c_f = 0{,}571\,D;$$

ratio of step of spin to diameter of tube –

$$\varphi = \frac{\pi}{\operatorname{tg}\alpha}.$$

Corresponding to the two values of speed of sound, we obtain $q_e = 3.16$ and $q_f = 2.99$. Experimental values lie near the calculated values (see below, Table 3).

Frequency of spin is determined from the relation

$$\nu_{kn} = \frac{\lambda_{kn} c}{2\pi}; \qquad (2.41)$$

frequency of spin in a volume with a concentric insert for the case $\frac{R_0}{R_1} < 4$ is determined by the following approximate formula [32]:

$$\nu = \frac{c}{\pi (R_0 + R_1)}. \qquad (2.42)$$

Table 3.

Index		Diameter of tube, mm											
		3,62	14,5**		14,7*				22,0**		23,0**		25,4
		Diameter of insert, mm***											
		0	0	6,0	0	5,0	8,3	9,5	0	13,0	0	4,0	0
Frequency, kilocycles	Experiment	148	38,2	29,6	39,4	32,6	31,5	28,3	25,6	17,1	23,9	21,5	23,0
	Theory	152	37,9	29,3	37,3	30,3	26,0	24,7	24,9	17,1	23,9	22,1	21,6
Ratio of step to diameter	Experiment	3,23	3,12	4,03	2,98	3,61	3,73	4,15	3,07	4,60	3,15	3,50	2,96
	Theory	3,15	3,15	4,07	3,15	3,88	4,52	4,30	3,15	4,60	3,15	3,40	3,15
Source of experimental data		[3]	[34]	[34]	[3]	[3]	[3]	[3]	[34]	[34]	[25]	[25]	[3]

*Experimental values of frequencies are calculated by ratios of step to diameter which were given in the work of Manson [30], which is in the literature list to Chapter II.

**Experimental values of ratio of step to diameter are calculated by the frequencies given in the indicated works.

***Frequencies of spin for experiments with inserts were calculated by the approximate formula (2.42)

where R_0 – radius of tube;

R_1 – radius of concentric insert.

In point of fact, Manson found only natural frequencies of transverse oscillations of gas behind the detonation front; the cause of appearance of such oscillations remained unexplained. Furthermore, in the theory of Manson, there were not at all considered longitudinal waves, although they indisputably can affect transverse frequencies.

An important contribution to the understanding of the nature of the trail was made by Chu Boa-Teh [33]. Let us consider certain of the most important results of his work. Chu Boa-Teh investigated small linear oscillations of parameters of the gas near average values. p_1, ρ_1, T_1, determined by the state of the gas behind the detonation front. Let us select cylindrical system of coordinates r, θ, z, which

is connected with the detonation products. Let us assume that axis z coincides with axis of pipe and is directed in the direction of the front. Then relative to the selected reference system the detonation front moves with velocity u_1, and its position is determined at any moment of time by the relation $z = u_1 t + \zeta(r, \theta, t)$. ($\zeta$ designates a certain small deviation of the surface of the front from the average position).

As Chu Boa-Teh showed, the influence of some source of disturbances rotating in plane $z = 0$ with angular velocity ω on the gas behind the detonation wave front can be written in the form

$$h(r, \theta, t) = \sum_{k=-\infty}^{\infty} \sum_{n=1}^{\infty} h_{kn} e^{ik(\theta - \omega t)} J_k(\lambda_{kn} r). \tag{2.43}$$

Inasmuch as there is formulated a linear problem, it is sufficient to consider the influence on the gas of one of the components of this perturbation. The wave generated by such a component in the region $z < 0$ is written

$$\frac{\delta p}{\gamma_1 p_1} = \frac{\gamma_1 - 1}{2\gamma_1} \cdot \frac{h_{kn}}{\rho_1 c_1} \cdot \frac{1}{\sqrt{1 - \frac{\omega_{kn}^2}{k^2 \omega^2}}} e^{ik(\theta - \omega t - \varkappa z)} \times J_k(\lambda_{kn} r). \tag{2.44}$$

Here h_{kn} — constant coefficient, determined by properties of the source;

δ_p — deviation of pressure from average level p_1;

k and n — integers;

R_0 — radius of pipe;

c_1 — speed of sound behind detonation wave front;

ω_{kn} — natural frequency of transverse oscillations, which satisfies the relation

$$\omega_{kn} = \lambda_{kn} c_1. \tag{2.45}$$

The value of κ can be determined from equation

$$\kappa = \frac{\omega}{c_1}\sqrt{1 - \frac{\omega_{kn}^2}{n^2\omega^2}}. \tag{2.46}$$

Behavior of wave (2.43) in region $z < 0$ depends on the relationship between ω_{kn} and $n\omega$. If $n\omega > \omega_{kn}$, we have an undamped wave propagating along z. With approach of $n\omega$ to ω_{kn} the wave depends on z less and less; for $n\omega = \omega_{kn}$, $\kappa = 0$ and oscillations become purely transverse.

When $n\omega < \omega_{kn}$, the quantity κ becomes imaginary and in the exponent of the exponents function there appears a real part. It is possible to see that in this case the wave constitutes transverse oscillations attenuating along z. For fixed $\omega < \frac{\omega_{kn}}{n}$, the wave attenuates by e times at a distance of $z_0 = \frac{1}{n\kappa}$.

Further, Chu Boa-Teh considers the gas behind the supercompressed detonation wave ($u_1 < c_1$). If from the region after the front there is incident a sonic disturbance onto the detonation wave of the following form:

$$\frac{\delta p}{\gamma_1 p_1} = A_{kn} e^{in(\theta \quad \omega_1 t \quad \kappa_1 z)} J_n(\lambda_{kn} r), \tag{2.47}$$

that the wave reflected from the front will be described by expression

$$\left(\frac{\delta p}{\gamma_1 p_1}\right)_{\text{отр}} = B_{kn} e^{in(\theta \quad \omega_2 t \quad \kappa_2 z)} J_n(\lambda_{kn} r). \tag{2.48}$$

Here A_{kn} and B_{kn} are constants determined by the boundary conditions; κ_1 and κ_2 are given by relationships

$$\kappa_1 = \frac{\omega_1}{c_1}\sqrt{1 - \frac{\omega_{kn}^2}{\omega_1^2}}, \tag{2.49}$$

$$\kappa_2 = \frac{\omega_2}{c_1}\sqrt{1 - \frac{\omega_{kn}^2}{\omega_2^2}}. \tag{2.50}$$

It is possible to show that $\omega_2 = \omega_{kn}$, if $\omega_1 = \omega_{kn}$, and that

$$\omega_2 = \frac{1}{\omega_1} \frac{\Omega^2 + M_1^2 \omega_{kn}^2}{1 - M_1}, \quad \text{if } \omega_1 \neq \omega_{kn},$$

where

$$\Omega = \omega_1 - \varkappa_1 u_1 = \omega_2 + \varkappa_2 u_1. \tag{2.51}$$

Quantity Ω is frequency of perturbations appearing on the front; M_1 is Mach number after the front.

From relationships (2.49) and (2.50) it follows that for $\omega_2 = \omega_1 = \omega_{kn}$ oscillations in both waves become purely transverse.

In the solution of Chu Boa-Teh, the form of the reflected wave does not depend on boundary conditions. Therefore, if on the detonation front for some reason there appears a perturbation rotating with angular velocity Ω and containing only one harmonic, the form of the wave generated by it in the gas will be analogous to (2.48). Let us note here that this will also be valid for $M_1 = 1$, inasmuch as such a value of M_1 is not peculiar to a wave proceeding from the front. During spin detonation, such a perturbation is a transverse front, and waves of type (2.48) form the trail.

It is necessary, of course, to consider that the transverse front radiates not only the basic harmoni but also frequencies, which are multiples of Ω (inasmuch as with respect to θ the phenomenon is period). In the linear theory, amplitude of oscillations of gas after the front tends to infinity, when frequency of the exciting force approaches resonant frequency ω_{kn}. It is possible to show that if the source of oscillations has a discrete spectrum of frequencies of form $n\Omega$, then resonance can be only at one frequency; i.e., if one of frequencies $n_*\Omega$ differs from one of the natural frequencies ω_{kn*} by $\Delta \to 0$, then all other $n\Omega$ will differ from corresponding ω_{kn} byfinite amounts. This it is easy to see from the fact that

λ_{kn}, which determine the value of ω_{kn}, form a monotonic increasing sequence such that $(\lambda_{k,\ n+1} - \lambda_{k,n})R_0 > 1$ and $\lim\limits_{n \to \infty} R_0(\lambda_{k,n+1} - \lambda_{k,n}) = 1$, while $n\Omega$ are frequencies equidistant from each other.

If we now assume that frequency of rotation of the perturbation on the front is close to a certain natural frequency ω_{kn}, we may assume that in the first approximation there are excited only oscillations, corresponding to this frequency. During one-headed spin detonation $n = k = 1$. With full coincidence of frequencies Ω and ω_{11}, the solution for the region behind the front constitutes an acoustic wave, which is parallel to the generatrix and which rotates with velocity Ω.

If coincidence of frequencies is incomplete, it is possible, by using the solution of Chu Boa-Teh to calculate angle of inclination of the trail to the generatrix of the detonation tube. According to equation (2.48), for $n = k = 1$ lines of constant pressure are given at a fixed moment of time by expression

$$\theta - \kappa_2 z = \mathrm{const}, \tag{2.52}$$

which determines spiral lines with step $\frac{2\pi}{\kappa_2}$. Angle of spiral with generatrix is given by the relationship

$$\varepsilon = \operatorname{arctg} R_0 \kappa_2 \tag{2.53}$$

or in terms of frequencies

$$\varepsilon = \operatorname{arctg} \frac{R_0}{c_1} \sqrt{\Omega^2 - \omega_{11}^2}. \tag{2.54}$$

Using (2.50) and (2.51), we can obtain the quadratic equation for ω_2:

$$\omega_2^2(1 - M_1^2) - 2\Omega\,\omega_2 + (\Omega^2 + M_1\omega_{11}^2) = 0. \tag{2.55}$$

For Chapman-Jouget detonation ($M_1 = 1$) we have

$$\omega_2 = \frac{\Omega^2 + \omega_{11}^2}{2\Omega}; \tag{2.56}$$

for $M_1 \neq 1$

$$\omega_2 = \Omega \frac{1 \pm M_1 \sqrt{1 - \frac{\omega_{11}^2}{\Omega^2}(1 - M_1^2)}}{1 - M_1^2} \tag{2.57}$$

(the plus sign is eliminated, inasmuch as $\omega_2 \leq \Omega$).

For a one-headed Chapman-Jouget spin detonation, by substituting (2.56) into (2.54), we obtain after simple transformations

$$\varepsilon = \operatorname{arctg} \frac{R_0(\Omega^2 - \omega_{11}^2)}{2\Omega c_1}. \tag{2.58}$$

Now it is easy to obtain an expression for ε in terms of speed of detonation, angle α of trajectory of head with generatrix and radius of the pipe. Frequency of rotation of head is determined by the evident relationship

$$\Omega = \frac{D \operatorname{tg} \alpha}{R_0}, \tag{2.59}$$

and natural frequency ω_{11} is established from (2.38). Putting these quantities in (2.[illegible]), we have

$$\varepsilon = \operatorname{arctg} \frac{D^2 \operatorname{tg}^2 \alpha - \lambda_{11}^2 R_0^2 c_1^2}{2 c_1 D \operatorname{tg} \alpha}. \tag{2.60}$$

Consideration of phototraces of spin detonation shows that if the trail is inclined to the generatrix, these angles of inclination are small. From (2.54) it follows that in this case frequencies Ω and ω_{11} almost coincide; i.e., oscillations almost do not depend on z. This explains the exceptional coincidence of frequencies calculated earlier by Manson with experimentally measured frequencies.

Detailed measurements of frequencies of the trail of the spin

detonation were conducted by R. I. Soloykhin and one of the authors [34, 35]. For the investigation there was used a method of photo-recording similar to that applied by Campbell. Photographing of the process was produced on film moving with speed of about 100 m/sec. Between the photographed object and the photorecorder there was installed a screen with a slot with width of about 1.5 mm located perpendicularly to direction of propagation of the detonation wave. In this case the trail was projected onto the film in the form of a luminous point being displaced in the opening of the slot. As a result of addition of motion of the image of the trail in the slot to that of the film on the latter there were traced certain curves, according to which, for known speed of the drum, it is possible to calculate speed of the luminous object itself.

For distinguishing the brightest luminous details, between slot and objective there was placed a dense blue light filter and there was used film RF-3, which possesses a spectral characteristic shifted to the region of blue rays.

In experiments there was used the mixture $2CO + O_2$, which was obtained by mixing commercial oxygen with carbon monoxide. Carbon monoxide was obtained by reaction of sodium formate with sulfuric acid. The mixture was held under water and was used not earlier than 4 hours after mixing.

Experiments were conducted in glass cylindrical tubes with diameters of 14.5 and 22 mm. For change of acoustic characteristics of the volume of gas, in a number of experiments on axis of tube there were placed concentric brass inserts with diameters of 6 and 13 mm.

Phototracings obtained in our experiments had the form of sine curves. Measurement of period of curves gives velocities of rotation

of the trail. Typical phototracings of the trail are shown in Fig. 35.

Fig. 35. Phototracings of trail of spin detonation in a round detonation tube. a) tube is not destroyed; b) tube is destroyed at a distance from the front of about 12 diameters of the tube.

Analysis of the phototracings showed that peripheral velocity of the trail in the case of tubes without concentric inserts is close to 1,730 m/sec.

Investigation of spin detonation by pressure transducers showed that changes of pressure in gas behind the front occur continuously, almost by a sinusoidal law, where amplitude, which attains in the initial stage of the process a magnitude $\approx 60\ p_0$, is lowered in 2-3 periods to a magnitude $\approx 30\ p_0$, after which it practically does not change until the end of the scanning; time of scanning is 400 µsec (Fig. 36).

Fig. 36. Oscillogram of pressure in the trail. Oscillogram time marks are every 10 µsec.

The continuous character of change of pressure at distances from the front exceeding the diameter of the pipe shows that the trail is not a shock wave.

Measurement, according to experimental data, of frequencies of rotation of the spin shows very good agreement with calculated natural frequencies. In Table 3 there are given results of comparison of theory and experiment according to our data and data of other authors.

Thus, it is possible to consider it to be established that the

trail formed after the head of the detonation is an antinode of tangential acoustic oscillations rotating with frequency determined by formulas (2.41) and (2.42).

With departure from the limits, on the detonation front there appear several heads. As we will see further on, for a many-headed spin, frequencies of rotation of the heads within definite limits also coincide well with that calculated according to acoustic theory.

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CHAPTER III

MULTIPLE-FRONT DETONATION

Definitions of Cyrillic Items in Order of Appearance

разр = dis = discontinuity

Ж = J = Jouget

ср = av = average

м/сек = m/sec

пл = pl = plane

мм = mm

§ 1. Nonuniformity of Detonation Front Far from the Limits

Noncorrespondence between the real structure of a detonation wave and the one-dimensional theory was revealed for the first time near the limits in the discovery of the phenomenon of spin detonation, which was considered in the preceding chapter. However for a long time there existed the conviction that spin phenomena exist only in a small region of initial conditions adjacent to the limit.

The impetus for further intense investigation of the structure of the detonation front was the application of the "trace" method. This method for the first time was used by Mach [1] for study of interactions of shock waves. It consists of the following: the walls

of a glass tube are covered inside by a smooth semitransparent layer of soot. If through such a tube there passes a shock or detonation wave with sharp nonuniformities in the front, then on the soot there remain traces of the motion of nonuniformities adjacent to the wall. There is also printed clearly the line of head-on collision of shock or detonation waves.

In 1957-1959 Yu. N. Denisov and Ya. K. Troshin with the help of the trace method established that the detonation front even of such easily detonating mixtures as $2H_2 + O_2$ and $C_2H_2 + 2.5O_2$ at all investigated initial pressures (up to 900 mm Hg) contains strong transverse perturbations, which trace on lateral walls of tube a network of intersecting helixes with identical step [2, 3, 4]. With increase of initial pressure, the number of lines is increased, and accordingly there decreases the average dimension of cells of the network formed by them. Traces of the nonuniformities are also imprinted on the sooty end of the tube. Characteristic imprints are shown in Fig. 37. The winding trace along the circumference of the tube, which is obtained as a result of encounter of the detonation wave with the shock, made it possible to conclude that the detonation front undergoes a break in the region of every transverse perturbation.

After the first experiments of Yu. N. Denisov and Ya. K. Troshin, we conducted a photographic investigation of the gas detonation front in tubes [5]. The scheme of the experiments is depicted in Fig. 38. Front of detonation wave AA propagating in the glass tube was photographed on moving film through a narrow slot. Angle φ between axes of the objective of the photorecorder and the detonation tube was 45° in one series of experiments and 90° in another series.

Distance between slot and objective was such that there was satisfied the relationship

$$D\sin\varphi = kv,$$

where D — speed of detonation;

k — ratio of reduction of objective;

v — speed of film.

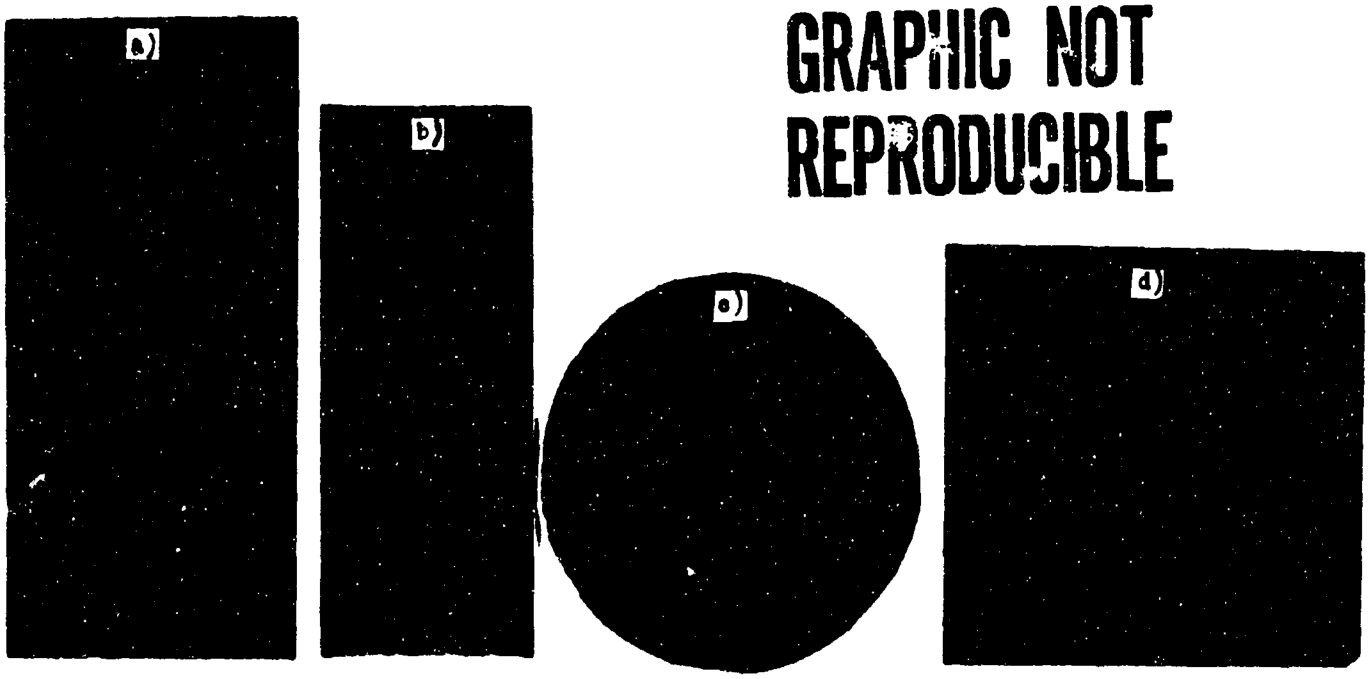

Fig. 37. Trace imprints of detonation waves on sooty walls. a) mixture $2H_2 + O_2$ (lateral wall of tube d = 45 mm, p_0 = 120 mm Hg), b) mixture $C_2H_2 + 2.5O_2$ (lateral wall d = 28 mm, p_0 = 25 mm Hg); c) mixture $C_2H_2 + 2.5O_2$ (end of tube, p_0 = 100 mm Hg, increased by 1.5 times) d) mixture $C_2H_2 + 2.5O_2$ (imprint on wall of spherical retort; p_0 = = 100 mm Hg, increased by 1.5 times.

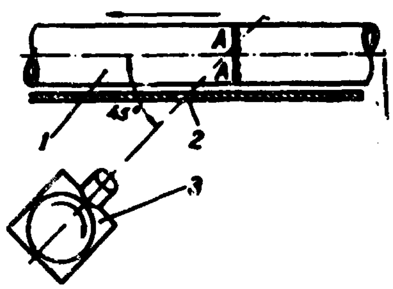

Fig. 38. Set-up of experiment during photographing of detonation wave front. 1) detonation tube; 2) screen with slot; 3) photorecorder - the arrow indicates the direction of detonation.

Photographs obtained in such a way (Figs. 39 and 40) differ from instantaneous photographs of the detonation front, since motion of film compensates for only the forward velocity of the front as a whole; however, separate details of its structure passing past the slot are photographed at consecutive moments of time; thus, their relative position can change.

Photographs made at $\varphi = 90^{\circ}$ in mixtures $C_2H_2 + 2.5O_2$ and $2CO + O_2 + 5\%\ H_2$ show that the the strongest luminosity is concentrated in a narrow layer adjacent to the front. Apparently, in this shell there burns practically all of the gas. In the plane of the front, luminosity is distributed nonuniformly: there are seen sharp nonuniformities in the form of a network of brightly luminous bands.

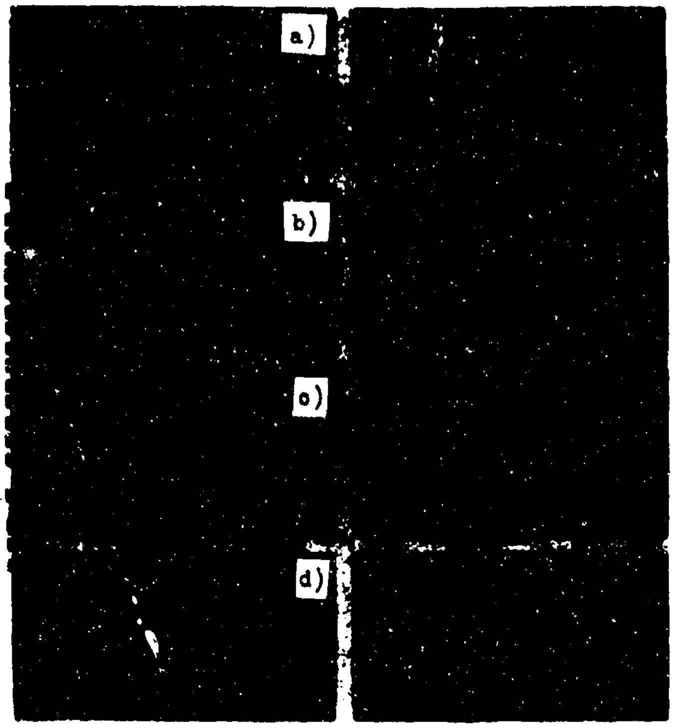

Fig. 39. Photographs of detonation wave front in mixture $2C_2H_2 + 5O_2$. a) p_0 = 6 mm Hg; b) p_0 = 9 mm Hg; c) p_0 = 15 mm Hg; d) p_0 = 35 mm Hg. On the left $\varphi = 45^{\circ}$; on the right $\varphi = 90^{\circ}$.

It is obvious that trace imprints on sooty walls of tube are formed as a result of interaction of nonuniformities observed on the photographs with the wall. By the angle between direction of trace and the generatrix of the tube one can determine speed of nonuniformities in transverse direction. It turns out to be between 0.6D and D, where D is speed of detonation, i.e., the considered nonuniformities are strong transverse perturbations propagating along detonation wave front. The bright glow of gas in the region of transverse

perturbation indicates ... of high temperature and intense chemical reaction. ... mixture in detonation wave occurs not in the plane ..., as one-dimensional theory of Zel'dovich assumed, but in separate narrow zones moving through the layer of gas adjacent to the ... front.

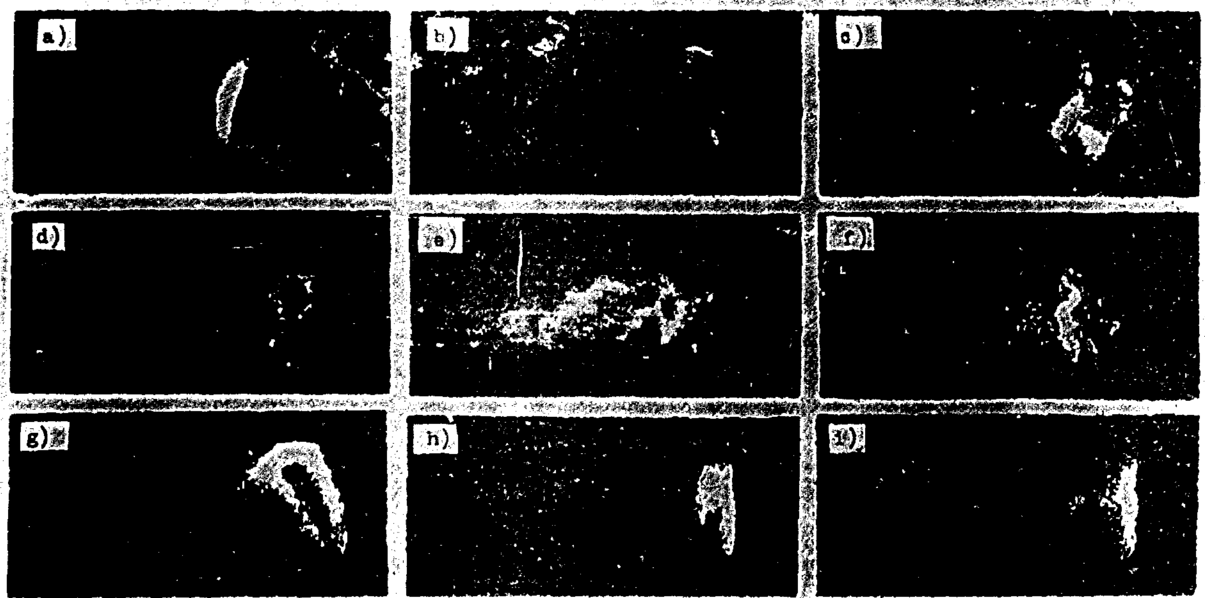

Fig. 40. Photographs of detonation wave front in mixture 2CO + + O_2 + 7[illegible] H_2. φ = 45°; a) p_0 = 40 mm Hg; b) p_0 = 65 mm Hg, c) p_0 = 90 mm Hg; d) [illegible] mm Hg; e) p_0 = 150 mm Hg; f) p_0 [illegible] mm Hg; φ = 90°; g) p_0 = [illegible] mm Hg; h) p_0 = 80 mm Hg; i) p_0 = [illegible] mm Hg.

V. P. Volin, Ya. K. Tr[illegible], G. I. Filatov and K. I. Shchelkin [6] revealed by the track method completely analogous nonuniformities in the spherical detonation front of mixture $2H_2 + O_2$. The detonation wave after departure from the narrow tube into a volume became a spherical wave. Upon collision with sooty glass plates the spherical front leaves precisely the ... traces which are obtained at the end of a tube. In Fig. 37c and ... there are given trace imprints of "plane" (in the tube) and spherical detonation fronts in mixture [illegible] + [illegible]$.5O_2$.

The last imprint is obtained on the sooty walls of a glass retort with diameter of 120 mm; ignition was produced in the center.

Nonuniformities observed in detonation front indicate that one-dimensional flow between plane shock front and Chapman-Jouget plane is unstable, i.e., small initial perturbations appearing due to different random causes are inadvertently increased and destroy the "normal" detonation wave.

The question of existence of gas mixtures in which the front of the independently propagating detonation wave is smooth (geometric form does not necessarily have to be plane) is of fundamental importance. Strong nonuniformities of the front were revealed in all mixtures investigated by us, and also by other authors [2-7]; $2H_2 + O_2$, $H_2 + 3O_2$, $2H_2 + O_2 + xN_2$, $C_2H_2 + 2.5O_2$, $C_2H_2 + 3O_2 + 15A_2$, $C_2H_2 + 2.5O_2 + xN_2$, $2CO + O_2$, $2CO + O_2 + xH_2$, $CH_4 + 2O_2$, where x changed within a wide range. However, the final answer to this question can be given only by a theory of stability based on data about the mechanism of the chemical reaction.

The question about stability of a plane detonation wave was investigated by K. I. Shchelkin [8] and R. M. Zaydel' [9] in the model represented in Fig. 41. It was assumed that during period of delay τ the rate of reaction is equal to zero, and upon the expiration of time τ the reaction passes instantly and state 2 is attained with a jump.

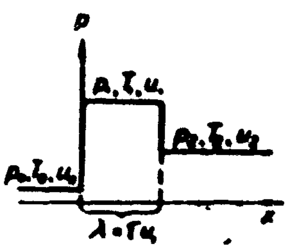
Fig. 41. Model of detonation wave according to [8, 9].

Qualitative reasonings of Shchelkin lead to the following: If combustion front ($x = u_1\tau$) is accidently distorted, then in protuberances turned in the direction of reaction products there occurs adiabatic expansion of gas which

has still not reacted from pressure p_1 to pressure p_2, which is accompanied by lowering of temperature and increase of period of delay. In protuberances, turned toward shock front, there appears local supercompression of reaction products as compared to undisturbed state 2; this leads to temperature rise and decrease of τ before the protuberance. Considering that instability occurs when change of delay of ignition due to adiabatic expansion of gas from region 1 to pressure p_2 is a quantity of the order of the actual delay, K. I. Shchelkin obtains the following criterion of instability of a plane detonation wave:

$$\frac{E}{RT_1}\left[1-\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]>1, \tag{3.1}$$

where E — activation energy.

For Chapman-Jouget detonation under normal initial conditions $\frac{p_2}{p_1} \cong 1/2$, and quantity γ which is average for states 1 and 2. is close to 1.3. Substitution of these values in inequality (3.1) gives

$$\frac{E}{RT_1}>6.7. \tag{3.1'}$$

The above presented considerations of K. I. Shchelkin, of course, are also valid for supercompressed detonation. However, they have a purely qualitative character, and the quantitative value of criterion (3.1) is doubtful.

R. M. Zaydel' conducted a more rigorous mathematical investigation of stability for the same model of the detonation wave for $u_2 \leq c_2$, i.e., for supercompressed detonation and Chapman-Jouget. The characteristic equation obtained by him has not completely been investigated, but from it there have been derived certain sufficient conditions of instability. In particular, for Chapman-Jouget detonation

$$\gamma M+(\gamma-1)N>\frac{2\gamma-1}{3\gamma-1}\left[2\gamma+\sqrt{2\gamma(\gamma-1)}\right]. \tag{3.2}$$

where

$$\gamma=\gamma_1=\gamma_2;$$

$$M=\frac{\partial \ln f(p,T)}{\partial \ln p}\Big|_{p=p_1,\ T=T_1};$$

$$N=\frac{d \ln f(p,T)}{d \ln T}\Big|_{p=p_1,\ T=T_1}.$$

Here f(p, T) is a function expressing dependence of chemical reaction rate on pressure and temperature.

The approximation of Zaydel' consists of the following: the gas in region 1 is considered to be nonreacting; kinetics of the reaction is taken into account only through the dependence of changes in τ in the perturbed front on M and N.

If chemical reaction rate is described by equation of type (1.19), then

$$M=m,\quad N=\frac{E}{RT_1};$$

substituting these values of M and N, and also $\gamma = 1.3$ into inequality (3.2), we will obtain

$$1{,}3m+0{,}3\frac{E}{RT_1}>1{,}9. \tag{3.2'}$$

Inequality (3.2') means that plane detonation front in the Chapman-Jouget regime in practically all gas mixtures is unstable. As it is known, in most cases the mechanism of gas reactions is the chain reaction. Effective activation energy of total reaction should be close to activation energy of that elementary reaction which is the basic supplier of active centers. For a reaction with unbranched chains this is the reaction of origin; with branched chains this is the reaction of branching of the chain. In all cases effective activation energy is several tens of kilocalories per mole.

Considering that RT_1 = 5,000 cal/mole (usually this value is less), we see that for a reaction of first order with respect to pressure (m = 1) inequality (3.2') is satisfied at E > 10,000 cal/mole, and for reaction of the second order (m = 2) — even at E = 0. Let us remember that inequality (3.2') was derived by Zaydel' only as a sufficient condition; the real boundary of stability, however, has not been found. Therefore, boundary values of M and N (and, consequently, n and E) can be less than those determined by inequality (3.2). Criterion of Shchelkin (3.1) gives considerably larger values of E; i.e., it covers a still smaller part of the real region of instability.

For supercompressed detonation, R. M. Zaydel' obtained also a certain sufficient condition of instability, but for small supercompressions it is not satisfied. Considering the question about influence of supercompression on stability of a plane front, we will use the criterion of Shchelkin which has more general character. With increase of speed D of detonation wave, temperature T_1 behind the shock front is increased approximately proportionally to D^2 and quantity $\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}$ approaches to 1. Therefore, the left side of inequality (3.1) rapidly decreases, and for a sufficiently high degree of supercompression the plane detonation front will be stable. This is clear from simple considerations: with increase of supercompression the detonation wave becomes similar in its properties to a shock wave, since released chemical energy composes a smaller and smaller fraction of the total internal energy of the gas behind the front; a shock wave without chemical reaction, as it is known [10], is stable.

For quantitative estimate of minimum speed at which plane front

For quantitative estimate of minimum speed at which plane front becomes stable, criterion (3.1) is unsuitable. Thus, R. E. Duff [7], photographing on motionless film the sooty wall of the tube at the time of passage through of a detonation of the mixture $C_2H_2 + 3O_2 +$ $+ 15A_2$ at $p_0 = 50$ mm Hg, recorded traces of transverse perturbations during supercompression with respect to speed of 1.75 times. For this case the left side of inequality (3.1) turns out to be considerably less than 1; nonetheless, the front turned out to be covered by transverse disturbances, just as in the absence of supercompression. Apparently, condition (3.1) for supercompressed detonation, just as for Chapman-Jouget detonation, is too strong; the real region of instability is considerably wider. Furthermore, it is possible to assume that near boundary of stable region there occurs unique hysteresis; i.e., if the supercompressed state corresponding to a smooth front which is stable relative to small initial perturbations is attained by gradual transition from the region of instability, then strong transverse perturbations can be retained without attenuating.

Instability of smooth front of detonation wave should be retained up to very high initial pressures of the mixture, quantities contained in inequalities (3.1) and (3.2) weakly depend on pressure. Nonuniformities of the detonation front are experimentally revealed by the track (or trace) method in mixture $C_2H_2 + 2.5O_2$ up to initial pressure of more than 1 kg/cm^2 and in mixture $2H_2 + O_2$ up to 3 kg/cm^2 [5, 6]. In the first case the dimension of nonuniformities was ≈ 0.1 mm, which was at the limit of resolution of the trace method. It is necessary to think that improvement of the method would permit us to observe nonuniformities also at considerably higher initial pressures.

With increase of initial temperature of mixture T_0, T_1 also increases; accordingly magnitudes of left sides of inequalities (3.1) and (3.2) decrease. However, up to very high values of T_0, the plane front remains unstable. Before the front of the spin transverse wave, temperature is about 1,100°K; behind the transverse shock front — about 2,800°K (transverse wave is supercompressed). Nonetheless, trace of transverse wave on sooty surface of tube during spin detonation of mixture $2H_2 + O_2$ reveals perturbations on the actual transverse front ([2-4]; see also Fig. 42). For mixture $2CO + O_2 + 5\%\ H_2$ nonuniformities in transverse front of steady-state spin detonation could not be detected by the authors. In the non-steady-state regime, when transverse front became anomalously wide, traces of nonuniformities in it were very clearly recorded.

Fig. 42. Trace imprint of spin detonation at p_0 = 25 mm Hg and d = 45 mm. Mixture is $2H_2 + O_2$. Traces of nonuniformity of the transverse front are conspicuous.

The above described instability of smooth detonation front appears only with respect to initial perturbations whose linear dimensions along the front are comparable with width of reaction zone $\lambda = u_1\tau$. R. M. Zaydel' showed that initial perturbations with dimension

$$\Delta y \gg \lambda \text{ or } \Delta y \ll \lambda \tag{3.3}$$

attenuate; i.e., with respect to them the plane front is stable. This result is understandable, since for $\Delta y \gg \lambda$, convex sections of the front are somewhat decelerated, and concave sections increase their speed, analogously to divergent and convergent detonation waves in conical tubes, and the front is smoothed; small-scale perturbations

($\Delta y \ll \lambda$), however, in plane of combustion front exponentially attenuate in the direction toward the shock front. The shock front itself is stable.

Stability of detonation wave with respect to large-scale perturbations is known from experiment: in tubes far from the limits of detonation ($d \gg \lambda$), the steady-state front always is perpendicular to axis of tube and is photographed as plane if nonuniformities comparable with λ are indiscernible on the film (see Fig. 39g, h and 40i); form of front of spherical detonation is close to geometric if we again disregard nonuniformities of the order of λ.

The plane detonational front should be stable in a tube whose diameter is considerably less than width of reaction zone. However, for $d \ll \lambda$, the detonation wave cannot propagate independently due to losses on the walls. Limiting diameters of pipes in which unsupported detonation still does not attenuate turn out to be comparable with width of reaction zone. Under these conditions plane front is unstable, which inevitably leads to formation of spin. With departure from the limits, the possibility of appearance of initial perturbations with dimensions of the order of λ is not all eleminated. Therefore, instability is retained.

In a more exact mathematical formulation, stability of a plane stationary detonation wave with respect to small perturbations was investigated by V. V. Pukhnachev [11]. Thus it was assumed that flow in combustion zone is described by the model of Zel'dovich (see Chapter I). Considering that small perturbations of flow represent superposition of cylindrical harmonics, he studied the behavior of a separate harmonic. In this case, equation of perturbed discontinuity surface has the form

$$z_{\text{возм}} = \varepsilon R_0 \exp(\nu R_0^{-1} c_* t + in\varphi) J_n(\lambda_{kn} r R_0^{-1}).$$

where μ is a complex parameter, and $|\varepsilon| \ll 1$.

The problem of detection of small perturbations is reduced to a certain eigenvalue problem for a linear system of ordinary differential equations. The presence among the set of eigenvalues of at least one with $\mathrm{Re}\mu > 0$ signifies instability of fundamental solution of equations of hydrodynamics and kinetics describing propagation of a plane stationary detonation wave.

It turns out that at $n = 0$, $\lambda = 0$ is an eigenvalue of the problem. The eigenfunction corresponding to the value $\lambda = 0$ described perturbation obtained by basic flow during shift of the front along axis z.

We will designate $\delta = x_0 R_0^{-1}$, where x_0 is effective width of chemical reaction zone.

Of great interest is the finding of eigenvalues with $\mathrm{Re}\mu > 0$ and the investigation of their dependence on the quantity δ. For this purpose there was conducted calculation on an electronic computer for the following values of parameters: $\frac{E}{RT_J} = 8$, $m = 1$, $\gamma = 1.2$.

Dependences of μ on δ, λ_{kn} is as follows:

$$\mu = \lambda_{kn} f(\delta\lambda_{kn}),$$

where f is a certain complex-valued function.

Fixing the value k = 1, we will designate $\mu_n = \lambda_{1n} f(\delta\lambda_{1n})$ and will set n = 1.

For $\delta = 0.475$ there exists eigenvalue with $\mathrm{Re}\mu_1 = 0$, $\mathrm{Im}\mu_1 = 1{,}887$. With increase of δ, value of $\mathrm{Im}\mu_1$ monotonically decreases, and value of $\mathrm{Re}\mu_1$ at first increases and then starts to decrease, and, finally, at $\delta = 1.35$, becomes equal to zero. Dependence of quantity μ_1 on δ is depicted in Fig. 43 by the solid line.

At $\delta = 0.557$, in half-plane $\mathrm{Re}\mu \geq 0$ there appears another eigenvalue, which disappears at $\delta = 2.15$. In Fig. 43, to this eigen-

value there corresponds the dotted line.

At $\delta < 0.475$ there are no eigenvalues with $\text{Re}\mu_1 \geq 0$, $\text{Im}\mu_1 \neq 0$. But if one we go over from $n = 1$ to $n = 2$, then we will obtain $\mu_2 = = \lambda_{12} f(\delta\lambda_{11} \cdot \lambda_{12}\lambda_{11}^{-1})$ and at $\delta = 0.475$, the quantity $\text{Re}f = 0.069 > 0$. With further decrease of δ the value of $\text{Re}\mu_2$ monotonically decreases, and at $\delta = 0.287$ becomes zero. In Fig. 43 this dependence is depicted by the dot-dashed line. At $\delta = 0.287$ there occurs transition from $n = 2$ to $n = 3$. With further decrease of δ, the described process can be continued without limit.

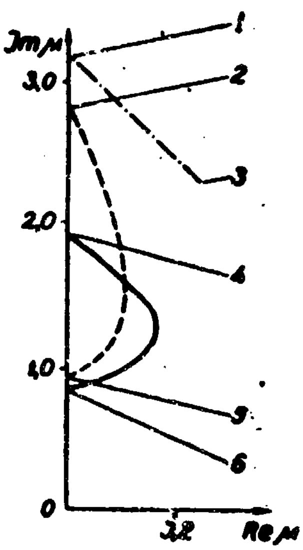

Fig. 43. Results of numerical calculations of instability of a plane detonation wave by V. V. Pukhnachev. 1) $\delta = 0.287$; 2) $\delta = = 0.557$; 3) $\delta = = 0.475$; 4) $\delta = = 0.475$; 5) $\delta = 2.15$; 6) $\delta = 1.35$.

Analogous calculations were conducted for $E = 0$ in a wide range of change of $\delta(0.35 \leq \leq \lambda_{11}\delta \leq 4.2)$. It turned out that in the region $\text{Re}\mu \geq 0$, $|\text{Im}\mu| \leq 6.2$, eigenvalues are lacking. However, excitation of oscillations of gas with very high frequency is physically doubtful. Thus, at low activation energies, the plane detonation wave is apparently stable.

It is interesting to note that at large values of parameter $\lambda_{kn}\delta$, eigenvalues with $\text{Re}\mu > 0$ do not exist. Hence, in particular, it follows that in a pipe of sufficiently small radius, a plane detonation wave in the considered model is stable with respect to small perturbations which are not one-dimensional.

In virtue of instability of one-dimensional detonation wave, there is produced a more complicated three-dimensional structure of the front with strong transverse perturbations. Near limits of detonation in the tubes there exists a single perturbation in the front — a spin transverse wave. Its structure is considered in Chapter II.

With departure from the limits, the number of transverse perturbations is increased. Subsequently, we will also call them transverse waves, without making beforehand any assumptions about their structure. Later it will be shown that their structure in many cases is analogous to the structure of a transverse wave during spin detonation.

Intersecting each other, transverse waves form in the front a characteristic network, which is imprinted also on sooty ends of the tubes. Comparison of trace imprints for different mixtures (see Fig. 33) shows that qualitatively they are completely identical. Consequently the structure of transverse waves in various mixtures is identical. The difference lies only in their characteristic dimensions. As the basic characteristic dimension we will select the average distance between transverse waves, moving in one direction along wall of tube. Let us designate it by a.

Quantity a is the most simple, and can be measured exactly by the imprints on side walls of the tube as the average distance between spirals in the direction perpendicular to the generatrix. On the end imprints or photographs of the front, the characteristic dimension is the average linear dimension of cells formed by the intersecting transverse waves. Average dimension of cells in detonation front is defined as the quantity a. Therefore, subsequently for the characteristic of any detonation with transverse waves far from the limits, including spherical waves, we will use quantity a, defining it as the average distance between transverse waves of one direction, or the average dimension of cells in the detonation front.

During steady-state detonation in a tube of sufficiently large diamemter, a depends only on composition and initial pressure of the

mixture. Influence of d becomes noticeable only when a is comparable with d. In Fig. 44 there are given photographs of detonation front of the mixture $C_2H_2 + 2.5O_2$ for identical initial pressure in tubes of various diameters. In the spherical detonation front [6] of sufficiently large radius, dimension of cells is the same as in wide tubes. This one may well see on photographs c and d of Fig. 37.

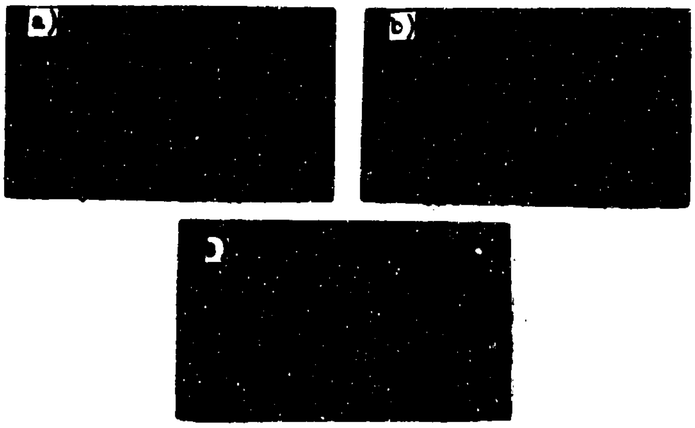

Fig. 44. Photographs of detonation front for identical initial pressure and various diameters of the pipe p_0 = 20 mm Hg. a) d = 15 mm; b) d = 21 mm; c) d = = 42 mm.

The dependence of a on initial pressure, which is constructed in logarithmic coordinates, is close to a straight line (Fig. 45). Analytically, it can be expressed by a formula of the form

$$a = \frac{A}{p_0^{\nu}}, \tag{3.4}$$

where A and ν are constants for each mixture.

Results presented in this paragraph show that under usual conditions, "normal" detonation with smooth front is not realized in virtue of instability, and the actual front contains transverse waves moving along it in different directions. Motion and collision of transverse waves causes local pulsations of the detonation front; therefore, Yu. N. Denisov and Ya. K. Troshin [9] called such a detonation "pulsating."* Apparently, to the essence of the

*The term "transverse wave" was not used by authors of works [2, 4, 6]. They called transverse perturbations "breaks" of the shock front or "oblique compression shocks" (OCS). As will be shown below, they imagined the structure of transverse perturbation not quite correctly.

phenomenon there would best of all correspond the term "multiple-front detonation," since along with the leading shock front there appears a set of transverse fronts, which burn the mixture after the secondary shock compression. This term we will use subsequently.

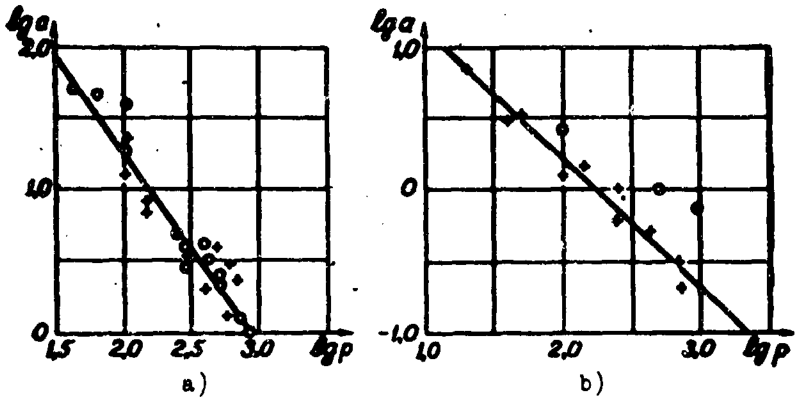

Fig. 45. Dependence of dimension of cells in tubes of large diameter on initial pressure (a — in mm; p — in mm Hg). a) mixture $2C_2H_2 + 5O_2$; b) mixture $2H_2 + O_2$; + are experiments of the authors, 0 are points according to works [2, 3].

The limiting case of multiple-front detonation in pipes, when there remains only one steady-state transverse wave, is one-headed spin.

§ 2. Motion and Structure of Transverse Waves During Multiple-Detonation

Transverse Waves in Flat Channels

Propagation of transverse waves in detonation front in general constitutes a three-dimensional non-stationary gas-dynamic process with chemical reactions whose kinetics for the majority of mixtures still has been little studied. Therefore, it is natural to investigate in the beginning simpler particular cases, and then to try to generalize them. Results of investigation of one of them — spin detonation — already have been presented in Chapter II. Now we will consider in detail multiple-front detonation in flat channels.

We will call a channel flat which is a narrow gap between two parallel plates. Magnitude of gap δ is chosen such, so that characteristic dimension of nonuniformities in detonation front exceed by a few times δ. During observance of this condition, flow of gas in detonation wave can be considered to be plane (two-dimensional), i.e., depending only on two spatial coordinates. Good results are obtained for

$$\frac{a}{\delta}=6 \text{ to } 10, \tag{3.5}$$

where a — average distance between transverse waves of the same direction.

For observation of the general picture of motion of transverse waves in a flat channel, very convenient is a mixture of acetylene with oxygen. Glow of transverse waves in detonation front of this mixture considerably exceeds the glow of the reaction products, due to this it is possible to photograph their trajectroies relative to walls of the channel by a usual camera with open objective [5] (Fig. 46). A series of such photographs in flat channels of different configuration is presented in Figs. 47 and 48.

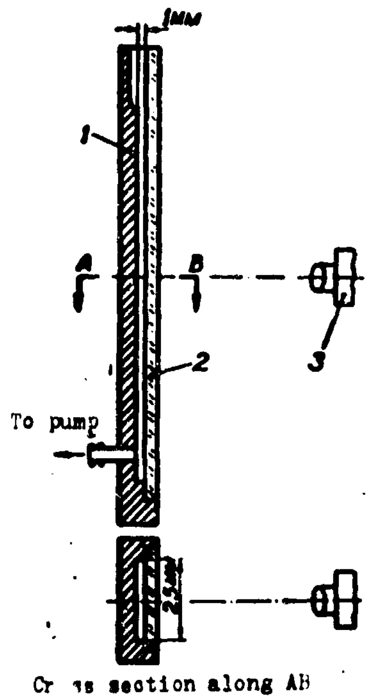

Fig. 46. Diagram of "flat" channel. 1) base of channel, 2) glass wall, 3) camera.

Every transverse wave shifts together with the front in direction of propagation of detonation, and simultaneously moves along the front in the transverse direction. Its trace is depicted on motionless film in the form of a luminous line, which forms angle α with direction of propagation of the detonation. There are two families of intersecting lines corresponding to transverse motion in two opposing directions; they form a

very regular network with diamond-shaped cells, absolutely analogous to the network of traces on the sooty walls of round tubes (compare with Fig. 37). Every transverse wave periodically undergoes head-on collisions and reflections. Intense glow of transverse wave not only at the time of collision, but also in intervals between them testifies to continuous combustion of the mixture in it. Tangent of angle α somewhat changes during the time between consecutive collisions; however, its mean value, equal approximately to 0.6, in steady-state detonation is identical along the entire length of the channel for lines of both directions, and almost does not depend on initial pressure of the mixture.

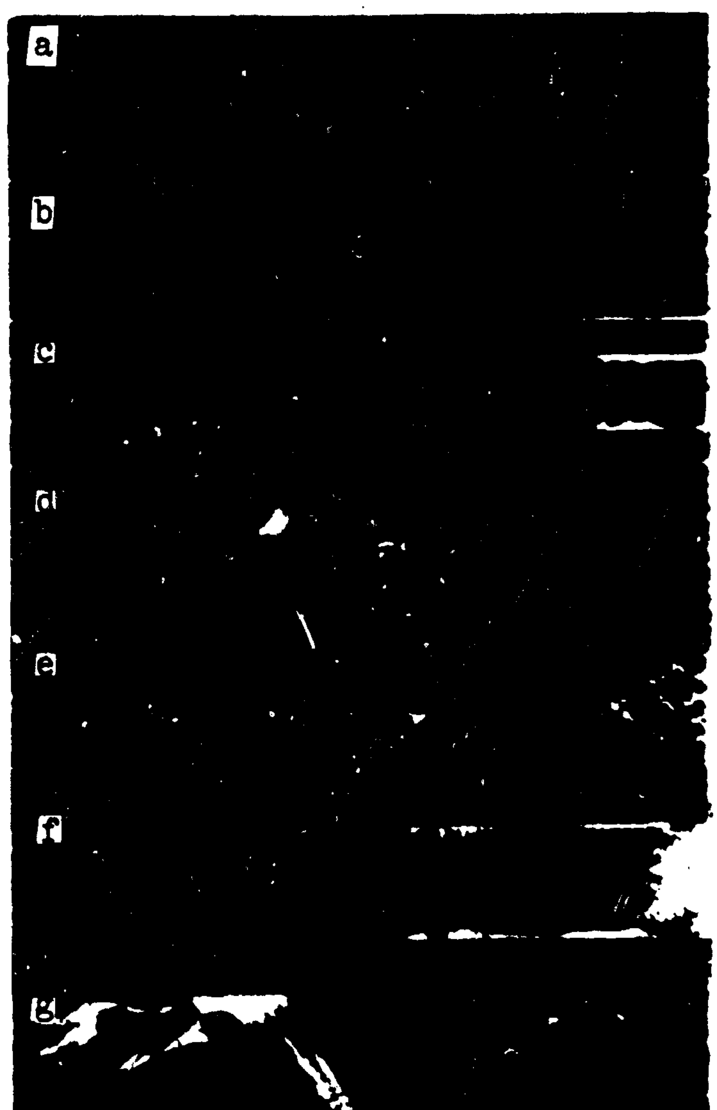

Fig. 47. Photographs of detonation in flat channels on motionless film. Detonation propagates from the left to the right.

With decrease of magnitude of gap at constant p_0, a increases, and speed of detonation is lowered. Deceleration, obviously, is due to the growth of relative losses on the walls. Increase of dimension of cells is caused by decrease of rates of chemical reactions due to decrease of temperature in the detonation wave. Furthermore, there is possible a direct influence of the walls on kinetics of reactions (for instance, destruction of active centers on the wall). With increase of the gap, a and D asymptotically approach thin limiting values, which are determined only by composition of the mixture and its initial pressure.

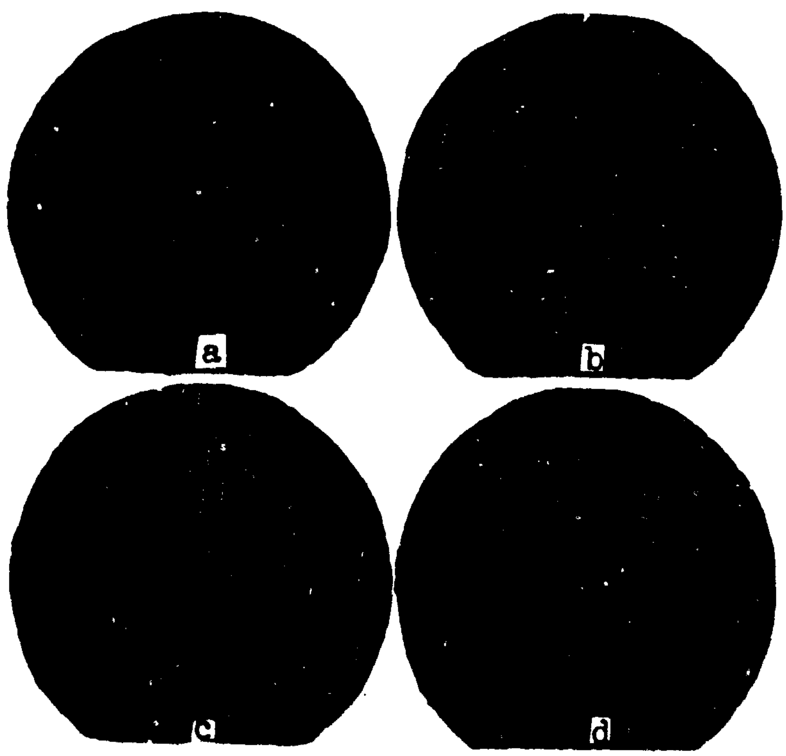

Fig. 48. Photographs of detonation in flat cylindrical channel (photograph 1 was made by R. I. Solovkhin).

Photographs in Fig. 47 and 48 also show motion of transverse waves in certain transient detonation processes. During propagation of detonation wave in a narrowing channel, dimension of cells of the network decreases, since detonation in this case becomes supercompressed and temperature after its front is increased. Supercompression, as

it is known [12], is maintained for a certain distance after the detonation wave leaves the narrowing channel and enters a channel with constant width. This can be observed by the change of dimension of the cells (photograph c in Fig. 47). In an expanding channel, cells are increased (photograph b). During flow of the detonation wave around an obstacle or a projection (photographs d and e), there are formed small regions where burning of mixture is carried out in transverse waves having only one direction, i.e., without collisions. After collision of transverse waves after the obstacle or reflection of these transverse waves from the wall after the projection, there is restored the former picture of motion.

The exit of a detonation wave from a narrow channel into a wide channel is accompanied by separation of transverse waves of various directions (photographs e and f in Fig. 47 and photographs b, c and d in Fig. 48). Thus if b/a, where b – width of narrow channel – is less than a certain magnitude $\left(\frac{b}{a}\right)_{min}$, and transverse waves, diverging to the sides, do not encounter the walls sufficiently closely, then the detonation attenuates. In the plane case

$$\left(\frac{b}{a}\right)_{min} \simeq 10. \qquad (3.6)$$

If, however, $\frac{b}{a} \geq \left(\frac{b}{a}\right)_{min}$, then after going into expansion the detonation wave becomes a divergent cylindrical (wave photograph b in Fig. 48).

Absolutely analogous phenomena are observed during exit of a detonation from a tube into a volume. S. M. Kogarko, N. N. Simonov and Ya. B. Zel'dovich established that minimum diameter of tube d_{min} at which there will be formed at the outlet a spherical detonation wave is related to effective thickness of detonation front in

the tube by the relation

$$\frac{d_{min}}{L} = const \approx 15. \qquad (3.7)$$

Here $L = \tau u_1 = \frac{ID\rho_0}{p_1\rho_1}$, where quantity I is experimentally determined momentum of the wave [13].

Comparing quantities d_{min} and L measured by Kogarko and others with dimensions of cells in the detonation front for several different mixtures (Table 4), we see that within limits of accuracy of measurements, the ratios $\frac{d_{min}}{a}$ and $\frac{L}{a}$ are identical for different mixtures:

$$\frac{d_{min}}{a} \approx 12 \qquad (3.8)$$

and

$$\frac{L}{a} \approx 0,8. \qquad (3.9)$$

Table 4.

Mixture composition	d_{min}, mm*	L, mm*	a, mm	$\frac{d_{min}}{a}$	$\frac{L}{a}$
$C_3H_8+2,5O_2$	2,5	0,16	0,2	12,5	0,8
$C_3H_8+2,5O_2+1,25O_2$	5,5	—	0,5	11,0	—
$C_3H_8+2,5O_2+2,5O_2$	12,5	0,77	1,0	12,5	0,77
$2H_2+O_2$	19	1,25	1,6	11,9	0,79
CH_4+2O_2	32	—	3,2	10,0	—

*According to [13].

Thus, for transition of detonation wave from channel with constant cross section into a wide region, in the two-dimensional as well as in the three-dimensional case, it is necessary that in the cross section of the channel there be contained a certain minimum number

of cells, and that effective thickness of detonation wave be proportional to average dimension of the cells.

The last result is understandable, since combustion of mixture is carried out in transverse waves, and thickness of detonation front can be considered to be of the order of average width of the transverse fronts, which, as we will see further on, is proportional to a.

Delay of development of detonation in the direction perpendicular to axis of tube for d close to d_{min}, which was noted in work [13], is due to the fact that outmost transverse waves, which bend around the edge of the tube, pass a considerable way without mutual collisions along the attenuated shock front, and chemical reaction in them dies down. Restoration of the detonational front occurs only after reflection of the attenuating transverse waves from external surface of tube. This process in the plane case is seen on the photograph of Fig. 48b.

Photographs of transition of combustion into detonation (see Fig. 47g and 48 d) show that transverse waves appear simultaneously with appearance of detonation.

In case of divergent cylindrical detonation, trajectories of transverse waves form two families of logarithmic spirals twisting in opposite directions [14] (see Fig. 48a).

Tangent of angle φ between the tangent to the spiral and the radius outside of a small region adjacent to the center is equal to 0.6 $\pm$ 0.06 i.e., speed of transverse waves along the front is the same as during steady-state detonation in a channel of constant width.

Mixture $C_2H_2 + 2.5O_2$ is very convenient for the described experiments due to high contrast of brightness of transverse waves against the background of general afterglow of the gas. Photographed network

of lines are also easily observed visually. For other mixtures, the general qualitative picture of motion of transverse waves is the same, but the obtaining of clear photographs of motionless film is not possible. More universal is the trace method.

In Fig. 49 there is given a trace imprint on the sooty wall of a flat channel which was left after detonation of the mixture $2CO + O_2 + 5\% H_2$. The impression was obtained in a channel with a gap between walls of $\delta = 4.7$ mm; thus the ratio $\frac{a}{\delta} = 5$.

Fig. 49. Trace imprint on wall of flat channel.

Besides the network of sloping traces, which are trajectories of transverse waves, on the imprints there are quite conspicuous also more smeared-out wavy horizontal bands located approximately at equal distances from each other. Comparison of imprints on both walls of the detonation channel shows that on the rear wall such bands are located exactly in the middle between bands on the front wall; i.e., with a shift by half of the distance between them. Sloping lines on both walls coincide. Obviously the flow of gas in this case is not absolutely two-dimensional and in the detonation front there exists some wave which is successively reflected from front and rear wall. After collision of such a wave with the sooty wall there remain horizontal bands. Distance between bands turns out to be approximately equal to 3.6δ and does not depend on value of a, which is increased with decrease of initial pressure of mixture. Hence it

is possible to calculate speed u_y of propagation of the considered wave between the walls:

$$u_y = \frac{2a}{\frac{3,6a}{D}} = 0,55D.$$

Form of horizontal bands characterizes profile of the leading front. With increase of ratio $\frac{a}{b}$, horizontal bands become less and less clear, i.e., oscillations of detonation front in direction of least dimension of channel weaken, and flow gradually approaches two-dimensional

Conditions of propagation of transverse waves in the radial gap between two coaxial tubes are close to those for the flat channel. Trace imprint on wall of external tube is shown in Fig. 50. Here there are also seen weak oscillations of the front along radius

$$\frac{a}{R_0 - R_1} \approx 10.$$

Structure of transverse waves in the two-dimensional case was investigated for the mixture $2CO + O_2 + 3\% \ H_2$ [15]. This mixture was selected because in the range of initial pressures convenient for laboratory experiments, 200-300 mm Hg characteristic components of the structure of the front have dimensions of the order of millimeters and centimenters, and can comparatively easily be resolved during photographing by the compensation method.

Fig. 50. Trace imprint on inner wall of outer pipe of coaxial detonation channel.

The detonation front propagated in a channel with rectangular cross section of 105 × 4.7 mm, length of

150 cm, whose last section was made from optical glass. The trace imprint shown in Fig. 49 was obtained in the given channel. For initial pressures of the mixture lying within the above-indicated limits, ratio $\frac{a}{b}$ was from 6 to 10°, therefore, flow differed little from plane flow.

Speed of transverse wave relative to gas behind the undisturbed shock front is strongly supersonic, therefore, whatever the structure of the wave is on the whole, the leading shock front should undergo a break at a certain triple point A moving together with the wave. The sharp upper boundries of traces in Figs. 49 and 50 are obviously trajectories of such triple points.

Subsequently, structure of transverse wave will be considered in a system of coordinates connected with point A. Therefore, it is necessary first of all to clarify how speed of its motion changes with respect to walls in intervals between consecutive head-on collisions of the transverse waves. Let us draw axis z in direction of propagation of detonation; x — in direction of the larger width of the channel. We have

$$\frac{u_x}{u_z} = \operatorname{tg} \alpha, \tag{3.10}$$

where u_y and u_z — components of velocity of point A;

α — angle between its trajectory and axis z.

For mean values there is satisfied the relation

$$u_{x\,cp} = u_{z\,cp} \operatorname{tg} \alpha_{cp} = D \operatorname{tg} \alpha_{cp}. \tag{3.11}$$

Speed of detonation D under conditions of experiment was 1710 m/sec for an initial pressure of the mixture of p_0 = 250 mm Hg, and 1730 m/sec for p_0 = 350 mm Hg. With accuracy sufficient for all subsequent calculations we will everywhere consider D = $1.7 \cdot 10^5$ cm/sec.

For the investigated mixture, measurements give

$$\mathrm{tg}\,\alpha_{cp} = 0.58 \pm 0.05 \qquad (3.12)$$

in range of initial pressures of 200-350 mm Hg. This spread exists for different waves in each experiment.

Trace imprints do not, however, make it possible to determine u_x and u_z in every phase between collisions. Such a possibility appears if there is known the trajectory of point A also in another system of coordinates, for instance, moving along axis x with constant speed V. Then we obtain one more equation for determination of u_x and u_z:

$$\frac{u_x - V}{u_z} = \mathrm{tg}\,\alpha', \qquad (3.13)$$

where α' is angle between trajectory of the point and axis z in the new system of reference.

Trajectories interesting to us can be obtained during photo-recording through a wide longitudinal slot of the propagation of detonation front of a film moving in the perpendicular direction. One of such phototracings is shown in Fig. 51.

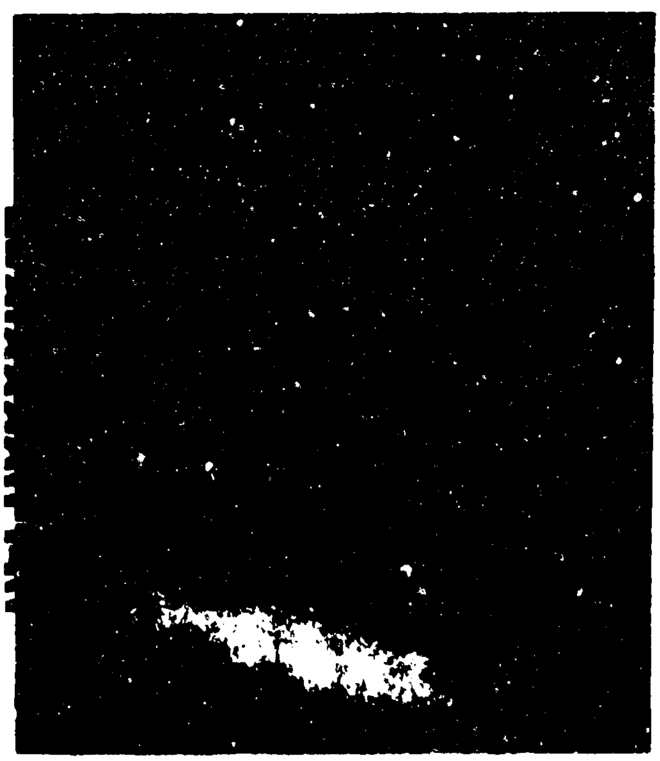

Fig. 51. Transverse scan of detonation in a flat channel; width of slot is 55 mm.

The segment of front bounded by edges of the slot illuminate on the film a wide slanted band, the tangent of angle of inclination of which to the vertical is equal to the ratio $\frac{V}{D}$, where V is equal to speed of film multiplied by the ratio of reduction of the

objective. Transverse waves, image is of which move in the same direction as the film, trace against the background of the band sharp lines, which coincide with trajectories of point A. Traces of opposing transverse waves are smeared out; their motion can be traced only by the brighter glow in places of collisions. After measurement of many photographs similar to those shown in Figs. 49 and 50, there were obtained the following dependences averaged over different waves and experiments: tan $\alpha(x)$, $u_x(x)$, $u_z(x)$ and

$u_0(x) = \sqrt{u_x^2 + u_z^2}$, which are represented in the form of graphs in Fig. 52; x is measured from point of collision; a – just as before – is the average distance between transverse waves with the same direction. On the average, every wave passes over the distance $\frac{a}{2}$ along axis x during the time between consecutive collisions. The graphs in Fig. 52 show that u_z changes from 1.4 to 0.8 D, and u_x changes from 0.4 to 0.66 D.

For investigation of the structure of a transverse wave there is applied the method of Toepler, which permits us to obtain photographs of compression shocks. In view of the large difficulties in creation of sufficiently short and powerful pulses of light for production of instantaneous schlieren photographs, there was used the compensation method. Photographing was produced through a slot of width 1.5 mm located at an angle of $30^\circ = \alpha_{av}$ to direction of propatation of the detonation. In such a position the slot was intersected by transverse waves

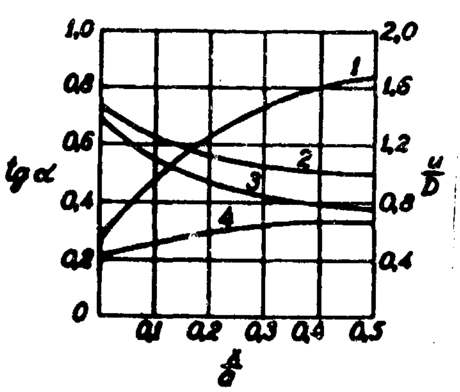

Fig. 52. Dependencies tan $\alpha(x)$ - 1, u_0/D - 2, u_z/D - 3 and u_x/D - 4.

with only one direction, where all were in the same phase between collisions with the opposing waves which moved parallel to the slot. Speed of film was established to coincide in magnitude and direction with average speed of image of transverse waves intersecting the slot.

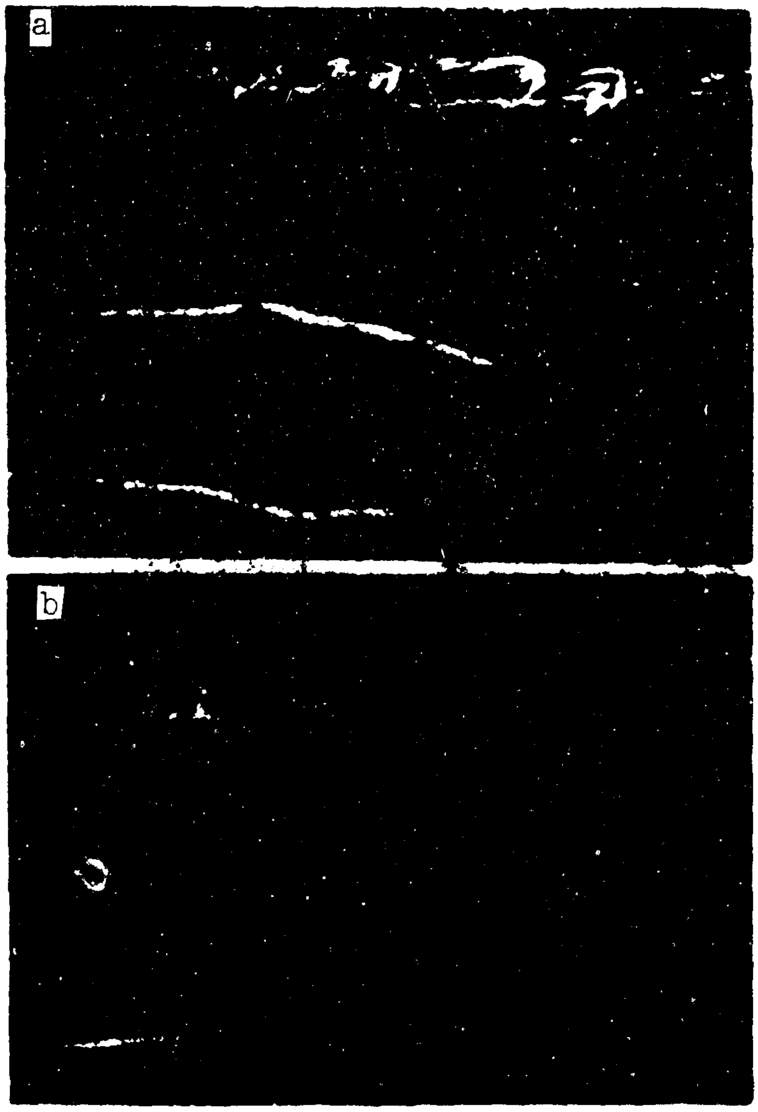

Fig. 53. Toeplergrams of transverse waves in flat channel. Angle of slot with axis z is equal to [illegible].

In virtue of the fact that motion of transverse waves in flat channel is not steady, as this occurs during spin detonation, photographs obtained by the described method (Fig. 53) differ from instantaneous photographs, since different elements of the wave intersect

the slot at different moments of time, in interval between which the relative location of these elements can be changed. Furthermore, true speed of transverse wave at the time of intersection of the slot can differ from the average speed; therefore, due to the difference in speeds of transverse wave and film, dimensions and angles of inclination of shocks are distorted if they do not coincide with slope of the actual slot. However, these small distortions do not change the qualitative picture of flow, and always can be taken into account during accurate analysis. The transverse front, which interests us first of all, has a slope close to the slope of the slot and is photographed practically without distortions.

In Fig. 53a, we see a series of transverse waves with the same direction in the last phase before collisions. In Fig. 53b, on the left — a transverse wave of the same structure, but bigger dimensions (initial pressure of mixture is lower). Configuration of shocks qualitatively does not differ from the case of spin detonation. The strong transverse front, which forms an angle of about 20° with direction of propagation of detonation, moves through the gas preliminarily compressed by the shock jump. Joining between them, just as during spin detonation, is realized through a "tip" containing 2 triple points. Certain transverse waves have different structure, as we see in Fig. 53b, on the right. Vertical dark lines on photographs — adjoining shock waves in burning gas to transverse front — are trails. Horizontal bright lines are traces of trails from opposing waves.

Before we go on to more detailed analysis of structure of transverse waves, we will also describe experiments on measurement of pressure. Two piezo-transducers, construction of which is described

in Chapter II, were imbedded in rear wall of detonation channel flush with its inner surface, so that the actual transducers did not introduce perturbations into the investigated flow. Simultaneously with oscillography of pressure there was produced photorecording of detonation wave through a narrow slot parallel to detonation front and located opposite the transducers on the front wall of the channel. Positions of transducers were noted by marks on the slot, which gave dark lines on the phototracings. Speed of film coincided with speed of image of the detonation wave.

Several phototracings with a set of the most characteristic oscillograms is shown in Fig. 54. Photograph a is interesting by the fact that on it there are fixed transverse waves in different phases between collisions: on the left — opposing transverse waves before collision; at right edge — immediately after collision; in center — intermediate phase. On photograph b in one of the convergent waves we may see cessation of ignition in the transverse front. On photograph c, distances between all neighboring transverse waves having both directions are identical, and head-on collisions occur simultaneously along the entire front. With such a regular process, in the width of the channel there is contained integer a/2. From every transverse front, in the direction of the burning gas, there stretch out long luminous trails. In examining of phototracings it is necessary to consider that angles between jumps here are strongly distorted. A shape of the transverse wave close to true can be obtained if its image is subjected to shear deformation in the horizontal direction in such a manner that the trail far from the front becomes vertical.

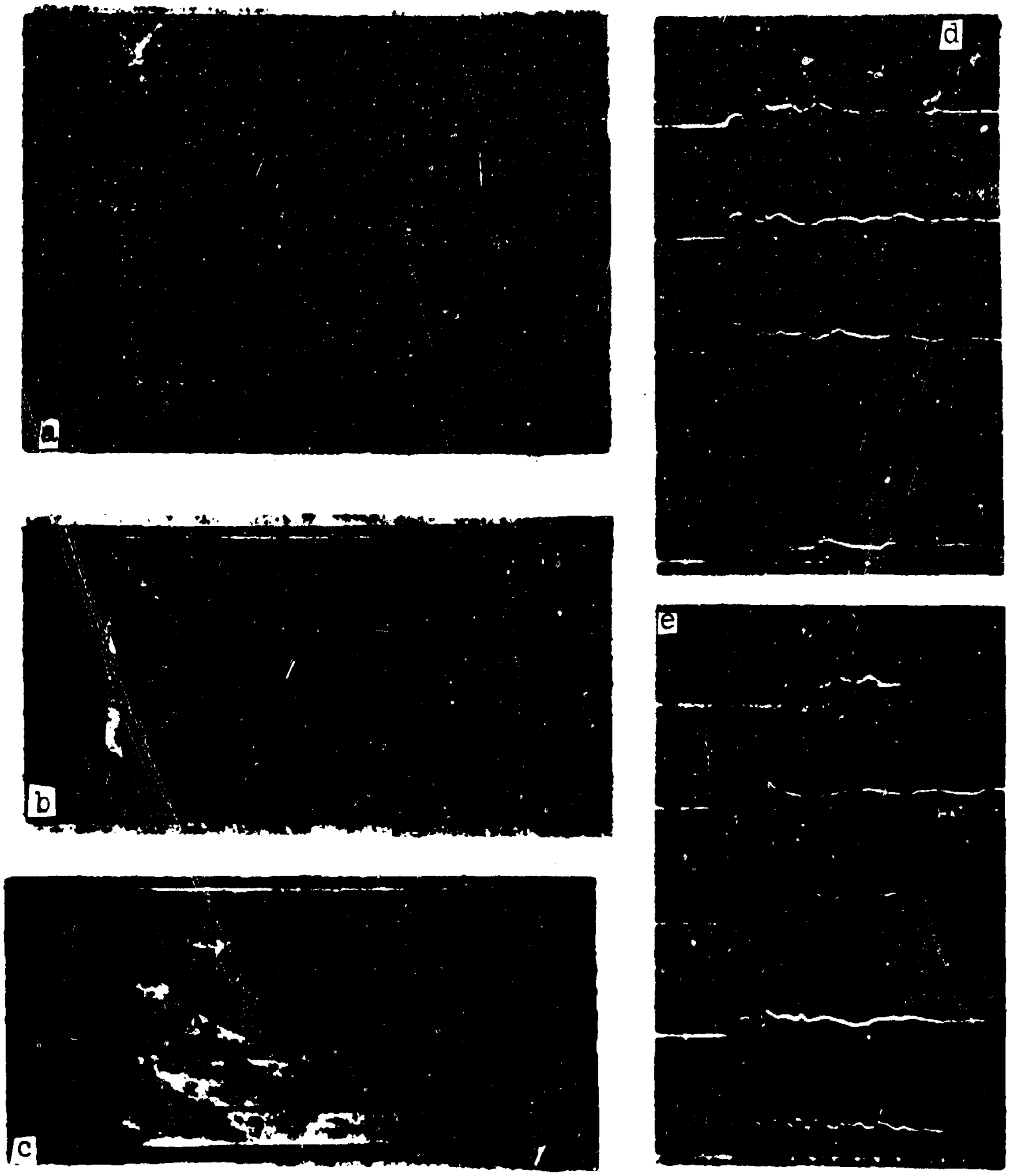

Fig. 54. Oscillograms of pressure in flat channel and corresponding trajectories of transducers on the picture of self-luminosity marks along the vertical are located every $20p_0$; along the horizontal – every 10 μsec.

Trajectories of pressure transducers corresponding to the given oscillograms (Fig. 54d) are plotted on the phototracing (Fig. 54a). Oscillograms and trajectories of transducers corresponding to them relative to the detonation wave are designated by identical figures. Lines 4 and 8 are left as marks opposite the transducers in the given experiment; the others are plotted according to the phototracings obtained in the same experiments.

Maximum pressure measured in the transverse wave was about 100 p_0, i.e., almost in 6 times greater than that calculated according to the classical theory of Chapman-Jouget, and 3 times greater than pressure after the shock front according to one-dimensional theory of Zel'dovich. At a distance on the order of a from the leading front, amplitude of pulsations of pressure sharply decreases, and average pressure practically coincides with that calculated by the Chapman-Jouget condition, which, taking into account correction for losses, is close to $17p_0$.

Gas-dynamic schemes of flow in the transverse wave, which correspond to those observed on schlieren photographs, are depicted in Figs. 55 and 56. Calculation is produced just as for the spin transverse wave. We will consider flow in a system of coordinates connected with point A, the motion of which is already known to us. Speed of incident undisturbed flow u_0 and angle α, formed by flow lines in this flow with axis z are given for every phase between collisions by graphs of Fig. 52. For calculation it is necessary to give one more parameter, for instance the angle β between front of shock wave A_2A "arriving"* at point A and axis x, which can be measured on schlieren photographs. By given values of u_0, α and β

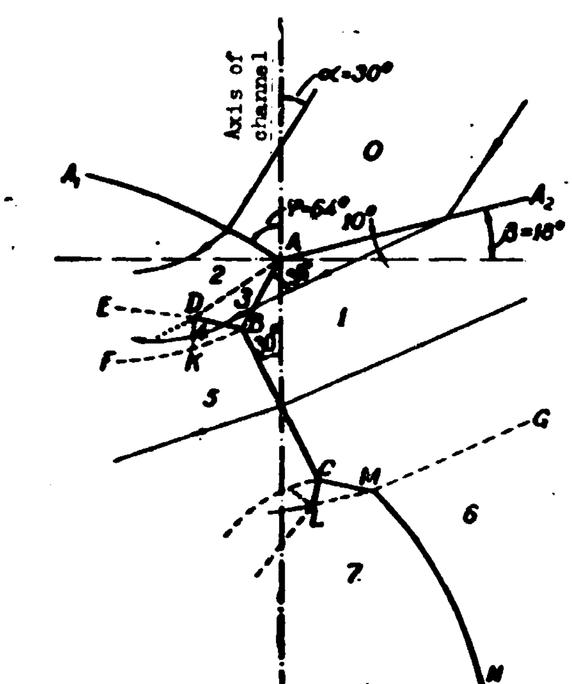

Fig. 55. Scheme of flow in flat channel with transverse wave. —— shock waves; ---- contact discontinuities; .... removable discontinuities; arrows indicate flow lines.

*An arriving wave, according to the terminology of L. D. Landau and Ye. M. Lifshits [16], is defined as a wave along whose front perturbations can propagate only in the direction toward the considered point.

there are calculated consecutively the triple configurations at point A and B.

We will consider at first the case when flow velocity after jump BD remains supersonic (see Fig. 55). After point D pressures on both sides of the contact discontinuity are equalized with the help of the centered rarefaction wave. Certain inaccuracies of the construction were discussed in Chapter II. Here it is necessary to consider further the transient character of real flow. Transverse wave considerably changes on the path a/2. During comparison of Fig. 53 with Fig. 55, it is clear that AB $\ll \frac{a}{2}$; therefore, in neighborhoods of points A and B flow differs little from steady-state flow corresponding to values u_0, α and β at the considered moment of time. At distances of the order of BC and larger, such an assumption is already illegal; therefore, difficulties of calculation of flow in the neighborhood of point C which are encountered during spin detonation are increased here. It is possible only to assume that near C there will be formed the same configuration of discontinuities as in the neighborhood of point B, as depicted in Fig. 55. Schlieren photographs show that boundary MG between burned and unburned gas is strongly blurred, obviously due to the turbulization of the combustion front, and the joining of shock waves CM and MN is realized not at corner point M, as is shown on the figure, but by a smooth transition.

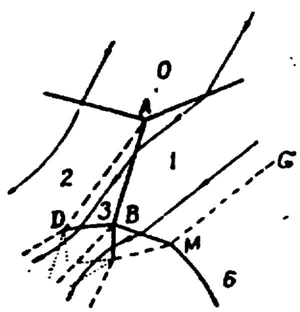

Fig. 56. Scheme of flow without transverse wave.

Jumps AA_1 and BC in spin transverse wave were considered to be detonational; here, however, in region 1, flow velocity calculated

by measured values of u_0, α and β turns out to be less than speed of Chapman-Jouget detonation. Therefore, jump BC, and together with it jump AA_1, which has approximately the same temperature after the front the same temperature after the front (close to total stagnation temperature), during our calculation must be considered to be purely shock, without release of chemical energy in the front. However, intense glow of gas behind BC and AA_1 (see Figs. 54 and 55) indicates the presence of ignition. The apparent contradiction is removed if we assume that in the case of a flat channel, the extent of the reaction zone after jumps AA_1 and BC is larger than distance AB. Then at triple points A and B fronts interact as shock fronts, flow of gas in region 2 is compressed from region 4, and flow in region 5 is expanded to the sides before maximum liberation of heat is attained. With such an assumption, speed of propagation of front AA_1 through state 0 should be greater, and speed of front BC through state 1 should be less than calculated by the Chapman-Jouget condition, which corresponds to reality. The whole complex consisting of shock jumps and reaction zone, may be called the detonation complex.

But can such a complex exist as stationary? During usual multiple front detonation, transverse waves periodically collide with each other; therefore, they are non-stationary. Steady-state transverse wave with analogous structure is realized during one-headed spin detonation, but there flow is essentially three-dimensional. However, it is also possible to imagine a two-dimensional detonation front with one or several transverse waves, moving along the front in one direction, without collisions, in the narrow gap between two coaxial tubes.

One of the authors [15] set up special experiments. For on e-

tion of transverse waves with one direction along the circumference of the gap there were installed several guide ribs. Motion of waves was established by traces on the sooty surface of the outer tube. It was possible to obtain several spiral traces twisted in one direction, of precisely the same structure as the trace of a spin transverse wave. But after approximately 3/4 of a turn, from every trace there started to branch out weaker traces, which correspond to rotation in the opposite direction; then, after several head-on collisions, the latter were strengthened, and the entire picture of traces took on the usual character. In the narrow gap between the pipes it is not possible to create also a detonation front with one stationary transverse wave. With approach to the limit, detonation remains multiple-front detonation and is ceased without becoming stable one-headed spin. The described experiments show that in the plane case, the stationary transverse wave in the detonation front is apparently impossible.

Let us turn again to the scheme of flow in Fig. 55. Obviously, the necessary condition for stationary of triple configurations at points A and B is

$$M_4 > 1,$$

since otherwise rarefaction wave KDF overtakes shock front FF, pressure after BD and BC nera triple point B drops and point F is carried downstream along jump AB. Furthermore, perturbations from rarefaction wave can reach point B also through region 5, if flow in region 5 does not become supersonic earlier than point K, at which contact discontinuity BF intersects with the first characteristic going out from point D.

Directly after the shock front BC, flow is strongly subsonic; its transition through speed of sound can occur only as a result of compression, with subsequent expansion in the transverse direction (transition through critical section of flow tube — shape factor), or due to liberation of heat during chemical reaction (thermal factor). Certainly, these factors can act jointly. During spin detonation, front BC is a supercompressed detonation front, and therefore the highest possible release of heat is insufficient for achievement by the flow of speed of sound; due to this, in Chapter II it was necessary to assume compression of flow tube in the radial direction. In the flat channel and in the narrow radial gap between tubes, velocity of flow 1, flowing into front BC always turns out to be less than calculated according to the Chapman-Jouget condition for the one-dimensional case. Therefore, flow tubes in region 2 have to be expanded before maximum quantity of heat is released. Whether or not flow thus attains speed of sound before point K remains vague. In any case, stationary two-dimensional transverse waves of the considered type cannot be obtained in experiments.

Certainly, the causes can be different. For instance, instability of smooth front AA_1 which generates weak transverse perturbations of various directions (see Fig. 53b). This could cause failure during an attempt to obtain in the gap between the tubes a transverse wave, rotating only in one direction, since destruction of waves of one direction observed on trace imprints started from branching of the initially weak opposing perturbations. During one-headed spin detonation in tubes without inserts (or with thin inserts), detonation jump AA_1 is strongly supercompressed; therefore, according to the criterion of Shchelkin (3.1), it may be stable. Actually, for steady-

state spin it is not possible by either trace or photographic methods to reveal perturbations in front AA_1, although in front BC perturbations are established.

Let us now follow how structure of transverse wave will change if rarefaction wave reaches point B through region 4 (at $M_4 < 1$) or through region 5 (at subsonic speed of flow 5 opposite point K), see Fig. 55.. We will assume state of gas in region 1 to be uniform and constant in time. Let us assume that an observer is located in a system of coordinates whose velocity relative to particles of gas in region 0 (or 1) at a certain initial moment of time coincides with velocity of triple point A, and subsequently remains constant. It is clear that rarefaction wave will cause attenuation of shock jumps BC and BD; speed of the latter relative to the gas before them will decrease, and triple point B will move along jump AB, increasing its length. Simultaneously, triple point A will start to drift along A_2A, since front AA_1 is a supercompressed detonation front and can be supported only by expansion of gas from region 4 with higher pressure. (Splitting of leading front A_2A into AA_1 and AB is caused, in the end, by perturbations from transverse front BC, which propagate along oblique shock jump BD and then through subsonic region 2). For analogous reasons point C can be displaced along MC.

Thus, the entire transverse wave starts to lag behind our observer, and in a motionless system of coordinates its component of velocity along front AA_2 decreases. Thus, angles of inclination of all jumps and their dimensions change. Length AB should be increased, since, after again equalizing velocity of system of coordinates of the observer with point A, we discover that at the initial moment point B drifts relative to the observer along AB with a certain terminal velocity (jumps BD and BC are "consumed" by the rarefaction wave),

while point A is at rest relative to the observer. In other words, front BC attenuates faster than AA_1. After BC, temperature decreases faster and intense burning of the mixture is ceased earlier. Points B and C, due to lengthening AB, may tend to merge. As a result, there will be formed the structure depicted in Fig. 56. We will call it a structure of II-nd type, in distinction from the structure of I-st type in Fig. 55. Together with front BC, there also disappears high-temperature region 5. After jumps DB and BM there remains a "tail" relative to the cold gas.

The described processes indeed occur in a flat channel. Between consecutive head-on collisions, speed of transverse wave along the leading front decreases; with passage of time, dimension of the tip is increased; glow after the transverse front BC usually weakens. It is necessary only to add that state I before transverse front under actual condition of multiple-front detonation is not uniform and constant in time. Transducers passing through region 1 frequently reveal a certain pressure drop with distance from front A_2A. In accordance with this drop, normal velocity of front A_2A through state 0 and pressure p_1 directly after the front decrease in time. Furthermore, transverse front BC moves between collisions through an expanding band of unburned gas contained between shock front A_2A and combustion front GM; therefore, in spite of lengthening of AB (and possibility of MC), width of front BC is increased. Probably, in virtue of the last circumstance, during steady-state multiple-front detonation in a flat channel, transition to the structure of II-nd type cannot be observed. The authors have obtained several tens of schlieren photographs for the mixture $2CO + O_2 +$ (2 to 5%)H_2, and have always discoverd only a structure

of I-st type. It was not clear on all photographs, but transverse front BC always was clearly distinguished, and its direction was almost perpendicular to flow lines in region 1. At the same time, on certain photographs of self-luminosity, transverse front is not seen at all (see Fig. 54b); this is apparently due to the cessation of ignition of gas after the strongly attenuated front.

The different structure of traces of transverse waves on trace imprints (see Fig. 49 and 50) also attracts attention. Part of the traces between intersections have the form of gradually expanding bands with sharp edges; their origin is clear: the upper edge is traced by triple points A and B in configuration of I-st type, the traces of which usually merge; the lower edge – by points C and M. The other part of the traces are single lines. It would be possible to assume that in the last case traces are formed by configurations of II-nd type, since in the projection onto the direction perpendicular to the trace, points A and B practically merge. But this assumption contradicts schlieren photographs, on which structure of II-nd type during steady-state detonation is not observed. Change of structure under the influence of soot on the walls (schlieren photographs can be obtained only with clean glass) is doubtful. It remains for us to assume that the lower triple points C and M do not always leave traces. On photographs of self-luminosity, breaks at points C and M usually are usually not clearly pronounced; this is due to the absence of a sharp boundary GM between burned and unburned gas. Boundary GM can be smeared out due to the presence along it of turbulent mixing, which is caused by difference between tangential velocities, and burning. Actually, contact discontinuity GM (more accurately, combustion front) was formed after burning of the under-

lying layer of gas by front A_1A of the preceding transverse wave, which imparted to the burning gas a velocity differing from velocity of the adjacent layer of unburned gas.

In order to better comprehend the general picture of motion of transverse waves in a flat channel, we will imagine a detonation front in which distances between all neighboring transverse waves of both directions are identical, and collisison occur simultaneously over the entire front. Scheme of motion of transverse waves in such an idealized two-dimensional case is depicted in Fig. 57. There are shown a profile of the leading front and the relative location of transverse jumps in four different phases between collisions. After collision, every transverse wave travels along front AA_1 of the opposing wave a distance of approximately 1/8a, before there appears a layer of unburned gas after it. At just this instant there is formed a configuration of I-st type. Subsequently its qualitative form is retained until the following collision.

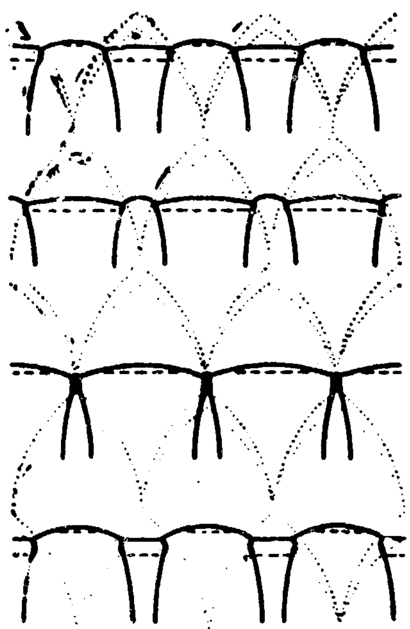

Fig. 57. Scheme of motion of transverse waves in flat channel. ——— second-order discontinuities; --- boundaries of burned and unburned gas; .... trajectories of end points of transverse front.

It is clear that the real structure of the detonation front is not so regular as it is depicted in Fig. 57. However, the tendency to regularity always exists due to the following circumstance: The fact is that the transverse wave is maintained at the expense of energy of the chemical reaction occurring in it. Therefore, if distance between some two neighboring transverse waves is increased,

then the rear wave will burn a wider shell of the unreacted mixture, will be strengthened and will start to overtake the leading wave. This reasoning remains valid also if we take into account head-on collisions.

During steady-state detonation in a flat channel, deviations of dimensions of separate cells from average magnitude a are small. In certain cases, especially when in the width of the channel there are packed a small number of cells, it is possible to observe a very regular structure (see Fig. 44b, c and Fig. 54c), which practically does not differ from that drawn on the diagram of Fig. 57. Average distance a between transverse waves of one direction (dimension of cells) is determined basically by the time of chemical reaction in the transverse wave.

It is of interest to follow how pressure, temperature and other characteristics of the gas in the region of the transverse wave change in different phases between collisions. Controlling parameters in calculation of triple configuration at point A for a gas mixture of given composition with given initial state (p_0, T_0) are velocity of undisturbed flow u_0 in system of coordinates connected with point A, and angle φ_0 between vector of this velocity and front of "arriving" wave A_2A, which is equal to $\frac{\pi}{2} - (\alpha + \beta)$. Sequence of values u_0 and φ_0 which the transverse wave passed over between collisions is depicted by the averaged curve 2 in Fig. 58. Dashed curves show limits of deviations of these quantitites from average. During construction of curves there were used graphs for u_0 and $\tan\sigma$ shown in Fig. 52; values of β corresponding to them were measured on schlieren photographs.

Triple configuration at point B can be calculated on the assumption that front AB is a straight line and that point B is motionless relative to A. In reality, the length of AB increases in time.

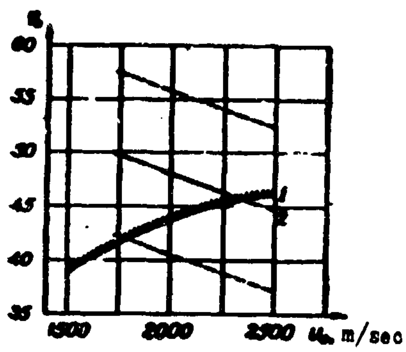

Fig. 58. Graph of change of u_0 and φ_0 for transverse wave in flat channel between collisions.

Calculation shows that flow velocity after jump BD remains supersonic only in a certain region of parameters u_0 and φ_0. Curve 1 in Fig. 58 is the boundary of this region (calculation is carried out for mixture $2CO + O_2$ at $T_0 = 293^\circ K$). Above curve 1 $M_4 < 1$ and stationary position of point B relative to A is known to be impossible, but speed of displacement of point B, as can be seen from experiments, is completely insignificant as compared to speed of incident flow from region 1. Therefore, correction to calculated magnitude, if we consider speed of drift will be obtained to be small, and it is possible to disregard it. This is all the more so because disregard of chemical reaction in region 2 and distortion of jump AB introduces apparently, greater errors.

Changes of pressures and temperatures after shock jumps AA_1, AA_2 and BC in the interval between collisions are represented on graphs of Fig. 59 and 60, where x is coordinate along general detonation front. During calculation there were taken values of u_0 and φ_0 along curve 2 in Fig. 58. All graphs start at x = 0, although the considered structure of the transverse wave during collision is destroyed, and appears again only at $\frac{x}{a} \approx 1/3$, when after the "arriving" wave there appears a layer of unburned gas. On earlier stages, real values of p ant T do not have to correspond to the given graphs. Pressure and temperature after all jumps monotonically decrease with increase of x.

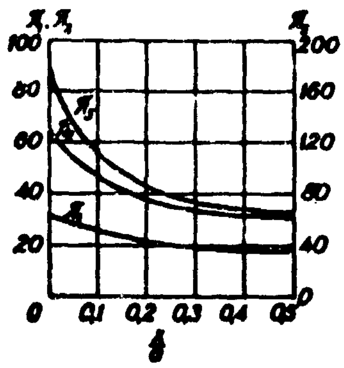

Fig. 59. Change of pressure in regions 1, 2 and 5 between collisions.

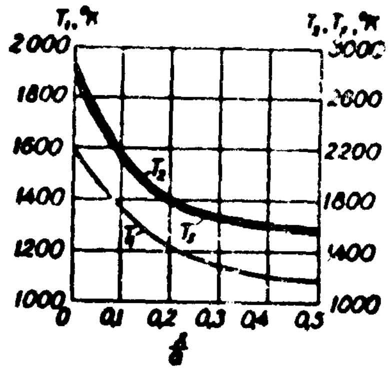

Fig. 60. Change of temperature in regions 1, 2 and 5 between collisions.

Table 5.

x/a	p_1/p_0		p_2/p_0		p_5/p_0	
	Calculated	Measured	Calculated	Measured	Calculated	Measured
0.2	21.6	23 ± 5	37.2	35 ± 10	81.5	80 ± 20
0.45	18.5	16 ± 4	32.3	30 ± 5	66.7	60 ± 20

In Table 5, for comparison, there are given computed and measured magnitudes of pressures after jumps A_2A, AA_1 and BC. Agreement between calculation and experiment is good. The considerable scatter of experimental values is because of the fact that not all transverse waves are identical; among them there are weaker, as well as stronger waves.

Just as during spin detonation, in experiments there is revealed a strong decrease of pressure along transverse front in the direction from B to C. Near point C, measured pressure after the front BC turns out to be approximately 1.5 times less than that calculated on the assumption of uniformity of flow in region 1 and of the absence in it of chemical reaction. Causes of change of pressure along BC were discussed in Chapter II.

Maximum local pressure is developed in region of collision of collision opposing transverse fronts; its calculated values is about 200 p_0*. Such high pulsations of pressure in detonation front were not registered by transducers, inasmuch as in not one of the experiments (there were about a hundred of them) did the transducer fall exactly between the colliding transverse fronts. This is fully explainable if linear dimension of region of high pressure in places of collision is of the order of 0.1a. In this case the probability that in 100 experiments the transducer will not once pass through the region of high pressure is about 50%.

Structure of II-nd type is observed in flat channel during transient detonational processes connected with local or general attenuation of the detonation front. Photograph b in Fig. 53 is obtained for transient detonation: toward the end of the channel, velocity of the front on the whole, number of transverse waves and their velocity along the front decreased. The wave on the right has the structure depicted in Fig. 56. The transition to structure of II-nd type occurs especially clearly during flow of detonation wave around an obstacle or step. When after the body there are formed regions with transverse waves of only one direction, and head-on collisions are absent for a long time. A photograph of transverse waves in a detonation front flowing around a step obtained by the compensation method is shown in Fig. 61. Configuration of flat channel and location of slot are shown in Fig. 62.

In center of photograph in Fig. 61 there are visible two transverse waves of I-st type; the remaining waves are strongly attenuated

*If we consider a certain layer of gas after front BC to be nonreacting, and the reaction after jumps diverging after collisions to be instantaneous, then this pressure turns out to be equal approximately to 210 p_0. If, however, divergent jumps remain purely shock jumps, calculated pressure of collision is about 180 p_0.

and have structure of II-nd type. With increase of distance of slot from end of narrowed part of channel, waves of I-st type completely

Fig. 61. Transverse waves in detonation front flowing around a step.

disappear, and again appear only after reflection of the attenuating transverse waves of II-nd type from the wall after the step simultaneously with retoration of normal velocity of the detonation wave as a whole. Apparently, analogous phenomena occur during exit of the detonation wave from the tube into a volume. After jumps BD and BL in configurations of II-nd type there stretches a long "tail"

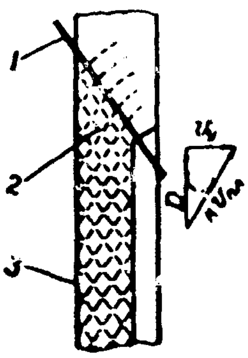

Fig. 62. Set-up of experiment during photographing of transverse waves in detonation front flowing around a step. 1) slot; 2) trajectories of transverse waves; 3) flat detonation channel.

of comparatively cold gas, which gradually burns in thr turbulent flow (see Fig. 53b and 61). Its glow is considerably weaker than that of the gas after jump AA_1. It is easy to show that transverse wave with structure of II-nd type also cannot be stationary. If it were stationary, then the basic perturbation generating the entire configuration would be jump AA_1, with high temperature and fast chemical reaction. In wave of I-st type, the leading front is transverse front BC; "break" of leading front AA_1 can be considered to be the "departing jump," which appears during flow around contact discontinuity ADE; its velocity through the undisturbed gas is larger than D).

It is clear that in configuration of II-nd type, velocity of jump AA_1 relative to undisturbed gas cannot exceed velocity D of

Chapman-Jouguet. Component of velocity of transverse wave of II-nd type in direction of propagation of detonation u_z is alwasy smaller than D, since $u_z = u \cos \alpha$ and $u \leq D$, therefore, stationary waves of II-nd type would not ensure advance of the detonation front with velocity D. Consequently, they cannot be stationary. For the same reasons, transverse waves of II-nd type are especially characteristic for attenuating detonation.* The authors observed analogous structure also during one-headed spin detonation in a round tube (Fig. 63). Thus the velocity of detonation appeared to be lower than normal velocity (~1500 m/sec instead of 1,700 m/sec). However, the small length of the photographed section of pipe (18 cm at d = 2.7 cm) did not make it possible to establish if the process was stationary

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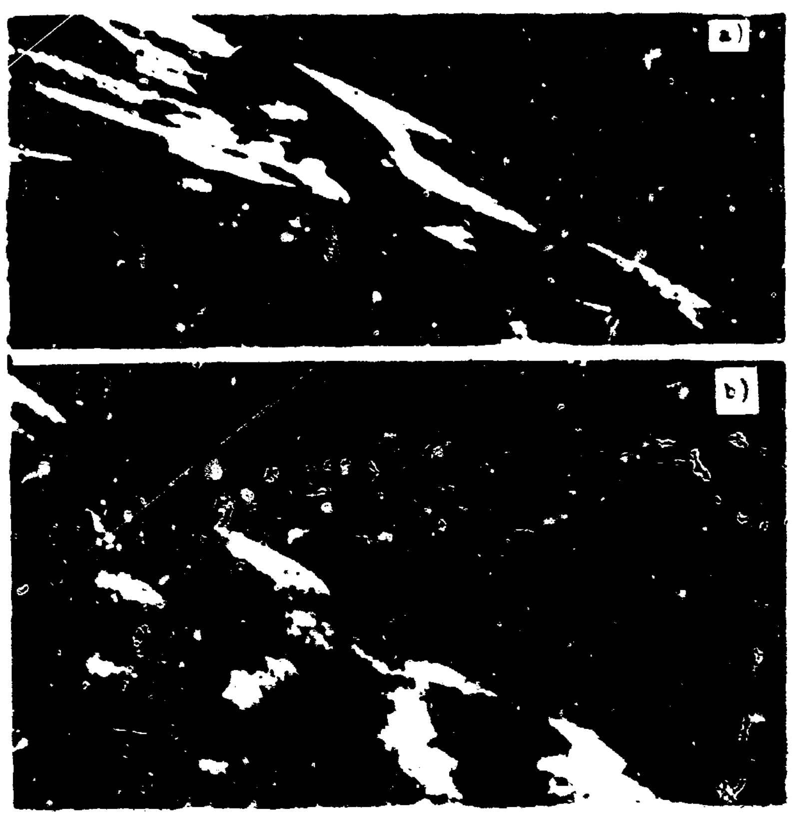

Fig. 63. Photographs of transverse wave before damping of spin detonation. a) Toeplergram; b) Self-luminosity.

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*Triple configurations in detonation front were considered also by Yu. N. Denisov, Ya. K. Troshin, K. I. Shchelkin and colleagues [2-4, 6] later than Duff [7]; however, all of them assumed the existence of only one triple point of type A, while considering AB to be the part of the trail adjacent to the front. In reality structure of transverse wave turns out to be considerably more complicated.

From the direction of the burning gas to every transverse wave there adjoins a trail. Near the transverse front the trail is a shock wave with pressure jump of up to half of average; this corresponds to a Mach number for normal velocity of incident flow of $M \simeq 1.2$. With increase of distance from the front, amplitude of pressure drops, and shock wave gradually becomes an acoustic wave. Change of pressure in the trail can be traced on oscillogram 10 in Fig. 54, which was taken during longer scanning. Form of the trail is seen from phototracings on the same figure. Its upper part (excluding the neighborhood of point M) is inclined approximately at the same angle as the transverse front; then, the trail becomes perpendicular to the detonation front, but with further increase of distance from the front, angle of inclination of trail to axis z (direction of propagation of detonation) changes sign, i.e., the trail starts to lag behind the transverse wave. This lag is understandable. As measurements show, average speed of transverse wave along the front is equal to

$$u_x = (0{,}58 \pm 0{,}05)\, D > C_ж,$$

where C_J is speed of sound in the Chapman-Jouget plane; the trail far from the detonation front constitutes an acoustic wave and propagates with velocity C_J. Lag of trail with increase of distance from front is strengthened also by decrease of speed of sound in reaction products due to the cooling influence of walls and the rarefaction wave.

Detonation in Pipes and Spherical Detonation

Experimental investigation of the structure of transverse waves in general of three-dimensional multiple-front detonation such as that performed in flat channels and for one-headed spin in tubes,

is still not possible. Therefore, it is possible to judge about structure only by indirect criteria, in particular on the basis of comparison of trace imprints. Transverse waves move through a narrow layer of gas adjacent to the detonation front, burning the mixture. We will consider their motion in the plane of the front.

In tubes, near the limits, detonation is one-headed spin, detonation, i.e., in the front there is one transverse wave accomplishing rotation along the circumference of the tube. In plane of cross section of tube it constitutes a stationary Mach configuration with a strongly developed leg (see Fig. 34). Incident and reflected waves adjoining the leg at the triple point are obviously shock waves, and their intensity drops rapidly with increase of distance from wall of tube.

Stable one-headed spin exists in quite a wide region of initial pressures of the mixture adjacent to the limit of detonation. Thus, in a pipe with Ø30 mm, for a mixture of $2CO + O_2 + 5\% \ H_2$, stable spin is observed for initial pressures from 40 to 75 mm Hg. Trace imprints on the end and side walls are identical for all pressures in this range. With increase of pressure above 75 mm Hg, the spin configuration loses stability: ignition starts after the incident wave: it is extended, accelerated (dimension of leg thus may be reduced) and with the other end reaches the wall ahead of the leg. After encounter of such a wave with the leg at a certain point of the wall there will be formed a divergent transverse wave covering the entire cross-section of the tube. Angle between ends of this wave and cylindrical wall changes with its propagation. Starting from a certain moment, at both ends there are formed Mach triple configurations, which then collide on the opposite side

of the cross-section of the tube, and the whole process is repeated (see end imprints in Fig. 64 and the diagram of motion of fronts in Fig. 65). Thus there occurs transition to two-headed spin. Spin heads, which leave a trace on the sooty inner surface of the tube and which are recorded by the photographic method are, thus, legs of the Mach configurations which move along the wall in opposite directions.

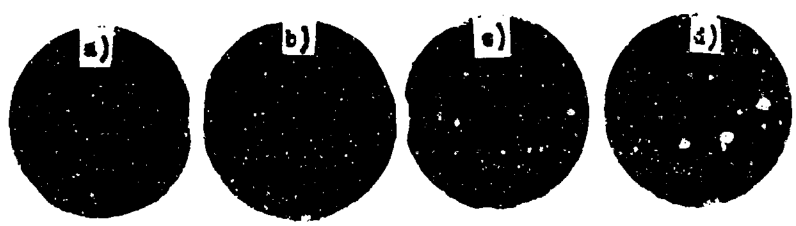

Fig. 64. Trace imprints on end of detonation tube. a) two heads before collision in pipe without insert; b) two heads after collision in pipe with insert; c and d) different stages of four-headed spin.

In round tubes without axial inserts it is not possible to obtain two strictly symmetric heads; rotation in one of the directions remains more intense. This fact was noted also by Duff [7]. Two symmetric heads are easily obtained in tubes with cylindrical axial insert with diameter of $d_1 =$ $= (0.2-0.5)d_0$, where d_0 is inner diameter of the pipe. However, in such a detonation channel it is not possible to obtain steady-state one-headed spin. Thus, for the mixture $2CO + O_2 + 5\% \ H_2$ at $d_0 = 30$ mm and $d_1 = 10$ mm, in the region

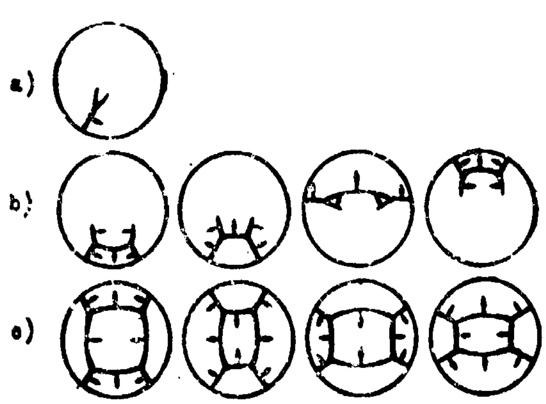

Fig. 65. Diagram of motion of fronts in plane of cross section of detonation tube. a) one-headed spin; b) two heads; c) four heads.

of initial pressures from 40 to 90 mm Hg, there is observed a stable two-headed regime (Fig. 66). At $p_0 < 40$ mm Hg, detonation is ceased.

The term "spin detonation" (the English word "spin" signifies "rotation"), strictly speaking, will be applied only for the one-headed regime,* since only in one case is there a transverse detonation wave rotating over the circumference of the tube. Already in the two-headed regime, the transverse wave moves through the entire cross section of the tube, striking alternately at diametrically opposite points. Legs of Mach configurations formed at the ends of this wave are mutually reflected after collision. With departure from the limits number of transverse waves in the detonation front is increased. Any detonation with transverse waves besides the one-headed spin, will be called multiple-front detonation. Terms "many-headed" or "n-headed spin," which are used in the literature, can be used only conditionally, if we understand by n the number of spiral lines traced by the transverse waves along the circumference of tube, or which is the same, the number of antinodes of acoustic oscillations of reaction products along the circumference of the tube. It is clear that we can not speak of "spin" regarding spherical detonation.

Fig. 66. Trace imprints of transverse waves. a) two heads in pipe with insert; b) four heads in pipe without insert

*Such an opinion is held by Yu. N. Denisov and Ya. K. Troshin [2-4].

Change of structure of detonation front in pipes with increase of distance from limits can be traced on the photographs in Fig. 11, 34, 37, 39, 40, 64, 66. Complete reconstruction of motion of transverse waves by trace imprints is also possible in the case of the four-headed regime in tubes without inserts. Successive phases of this motion are schematically depicted in Fig. 65c. Two trace imprints on the end are shown in Fig. 64.

Formation of triple Mach configurations during the interaction of transverse waves with each other or with the wall is characteristic for any multiple-front detonation. At first glance, the very regular network of traces on the sooty lateral walls of the tube at great distances from the limit may cause surprise. This cannot be explained if motion of transverse waves near the wall is assumed to be disordered. Ordered motion along walls obviously is created by the Mach legs formed during incidence of the transverse waves against the wall. Mach triple configuration appear also far from the walls during collision of transverse waves within a definite range of angles. On the regular network of traces drawn on the lateral walls by the legs, there are always superimposed very blurred disordered trace bands (see Fig. 37). Their appearance should be ascribed to collisions of transverse waves with the wall at angles less than limiting for formation of the Mach configuration. Externally these traces do not differ at all from horizontal bands in the flat channel, where there is no doubt about their origin* (see pp. 103-105).

*In works [2-4, 6], it is assumed that such traces are formed as a result of intense flashes of self-ignition in the region of symmetric or asymmetric collision of triple shock configurations of the type of the neighborhood of point A. Actually, in region of reflection of transverse wave from wall, especially with normal incidence, temperature is considerably higher than after the incident

Structure of trace left on sooty lateral wall of tube by Mach leg in the steady-state two-headed regime in tubes with axial insert is precisely the same as during one-headed spin. During detonation with large number of heads in different mixtures, traces of transverse waves moving along wall are completely analogous to traces in the flat channel, in spite of the fact that in round pipes near the wall transverse wave frequently is a leg of the Mach configuration, but in a flat channel at large value of ratio $\frac{a}{\delta}$, no legs are present. Structure of transverse waves during steady-state detonation in a flat channel, as was shown, does not qualitatively differ from the structure of a leg of a spin transverse wave. Similarity of trace imprints on lateral walls gives us a basis to consider that structure of transverse waves during multiple-front detonation in round tubes is the same. During transient detonation processes in flat channels, along with transverse waves having structure of I-st type, there were also observed attenuated transverse waves with structure of II-nd type.

Apparently, in a three-dimensional detonation front, transverse waves of II-nd type exist also during steady-state detonation, since here there always exist divergent transverse waves (with a front which is convex in the direction of propagation) attenuating considerably faster than in the two-dimensional case. Convergent waves, and also the formed Mach legs certainly must have structure of I-st type.

[FOOTNOTE CONT'D FROM PRECEDING PAGE].
wave; therefore, ignition of mixture under these conditions can be characterized as a "flash" as compared to the slower reaction in the incident wave. However, the considered traces are in no way related with places of head-on collisions of transverse waves moving along the walls, although during such collisions in reality "flashes" also occur.

Walls of pipe render an influence on motion of transverse waves only at distances from walls of the order of a. Therefore, a spherical detonation front of sufficiently large radius does not at all differ in structure from detonation front in pipes far from the limits. This was proven experimentally by Volin, Troshin, Filatov and Shchelkin [6]. Velocity of transverse waves along walls of pipe for different mixtures as $\frac{d}{a} \rightarrow \infty$, or, which is the same, $n \rightarrow \infty$, tends to (0.6-0.64) D, i.e., to the same magnitude as in the flat channels. Obviously, average velocity of transverse waves far from the walls and in the spherical detonation front should be the same.

Till now we have not been concerned with the question about what determines average velocity of transverse waves relative to the detonation front. Initially the authors assumed that after every transverse front there is satisfied local condition of Jouget, and, consequently, velocity of transverse front relative to gas before it should be equal to the velocity of detonation determined from calculation for local conditions [6, 17]. In case of a large number of transverse waves, it was assumed that their average velocity is somewhat less than detonation velocity due to head-on collisions, since after collision before each of the divergent waves the layer of compressed unreacted gas is initially narrow and is not able to detonate independently. Burning of mixture in it is supported only at the expense of a powerful shock wave, which has a velocity less than detonation velocity. It was assumed that with increase of width of the compressed layer, velocity of transverse front BC is gradually increased to a magnitude corresponding to the Chapman-Jouget condition. However, subsequent investigations showed that after the transverse front the Jouget condition is not satisfied.

During spin detonation of mixture $2CO + O_2$, velocity of the transverse front near the wall is larger than that calculated by the Jouget condition. Explanation of supercompression at the wall by the fact that the transverse front has finite dimensions along the radius, and therefore, that the Jouget condition should be satisfied somewhere after the middle part of the front, does not solve the problem, since it is not clear what determines the extent of the transverse front along the radius. During multiple-front detonation, speed of transverse waves is less than that calculated by the Chapman-Jouget condition. Head-on collisions do not explain the low value of average speed, since after collision the speed of divergent waves relative to the shock compressed gas before them not only does not increase, but, conversely, decreases.

Motion of transverse waves in detonation front turns out to be intimately connected with acoustic phenomena after the front From every transverse wave in the direction of the burning gas there departs a shock wave (MN in Fig. 55), which quite rapidly with increase of distance from the front is transformed into an acoustic trail. It is without doubt that formation of the trail is caused by perturbations proceeding from the transverse front. During detonation in tubes, acoustic waves moving along surface of tube have especially large amplitude. Leading heads of such waves are the legs of Mach configurations appearing during interaction of transverse detonation waves with the wall. Motion of heads is very ordered and close to periodic; therefore, waves generated by them in reaction products have to be well described by the solution of Chu Boa-Teh, which is the sum of harmonics of form (2.44), where the first index is a multiple of the number of heads.

In linear theory, the amplitude of those harmonics for which natural frequency of the volume (expressed in terms of λ_{kn}) coincides with the frequency of rotation of heads goes to infinity. Therefore, behavior of the trail is determined basically by harmonics having frequencies close to frequency of the heads. The most remarkable here is the fact that frequency of rotation of heads almost always turns out to be close to natural frequency of acoustic oscillations, with number of antinodes of pressure along the circumference equal to the number of heads, i.e., the tangent of angle α between trajectory of head and generatrix of the tube observed in experiments coincides well with that calculated by the formula (2.40). Such coincidence cannot be accidental. It means that average velocity of transverse detonation waves in detonation front is determined basically by velocity of propagation of acoustic transverse waves in reaction products. Analogous phenomena are observed in flat channels, where velocity of transverse waves only insignificantly exceeds speed of sound after the detonation front.

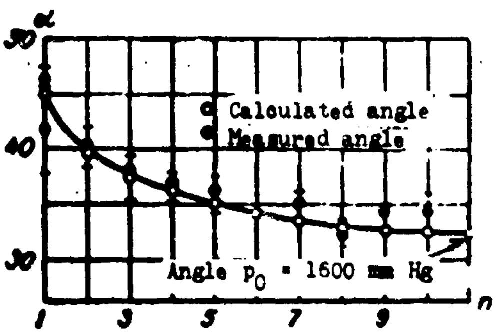

Fig. 67. Graph of $\alpha(n)$ according to Duff [7].

For comparison of measured values of α with those calculated by formula (2.40), where $\frac{c_1}{D}$ was considered to be equal to $\frac{\rho_0}{\rho_1}$, in Fig. 67, we present the graph of R. E. Duff [7] for the mixture $2H_2 + O_2$. Along the axis of abscissas there is plotted the number of heads n rotating in one direction. Very good agreement between calculation and experiment is observed for n from 1 to 4, if k in formula (2.40) is considered to be equal to one. The only exception is two-headed spin (n = 1, heads rotate in opposite directions), where measured

value of α is noticeably less than calculated. At $n > 4$ and $k = 1$, formula (2.40) gives values of α_{av} which are somewhat too low. Transition to different k is connected with a sharp increase of α_{av}, which in experiments is not observed. Let us recall that k is equal to the number of antinodes of pressure along radius in the corresponding monochromatic wave of form (2.44).

Real waves in reaction products can strongly differ from those considered; therefore, here we should not require full agreement between theory and experiment. It would be possible to calculate the limiting value of $\tan \alpha_{av}$ as $n \to \infty$ under the natural assumption that the space periods of acoustic oscillations along the radius and with respect to angle θ near the wall are identical. However, such an assumption for large n leads to strongly oversized values of $\tan \alpha$ as compared to the values 0.6-0.64 observed in experiment.

In spite of the fact that acoustic theory does not allow us to exactly predict for all cases the average velocity of transverse waves along the detonation front, the very strong influence of acoustic properties of burning gas on motion of transverse waves is without doubt. As. R. E. Duff noted [7], this fact subjects to doubt the satisfaction of the Jouget condition behind the real detonation front, according to which velocity of reaction products relative to the front is equal to the local velocity of sound, and consequently the front cannot "know" what occurs behind the Jouget plane. The influence of transverse motions of gas on the Chapman-Jouget condition will be considered in Chapter V.

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CHAPTER IV

STATIONARY DETONATION

Definition of Cyrillic Item

к = c = critical

The high speed of detonation processes causes the short duration of the phenomenon under usual conditions. Realization of a detonation process which is motionless relative to laboratory system of coordinates would make it possible to set up detailed investigations of structure of a detonation wave, distribution of density, pressure and temperature, kinetics of chemical reactions, and so forth, i.e., would serve as a powerful means of investigation of detonation processes. Furthermore, obtaining of a detonation wave in a stationary flow would permit us to obtain high rates of combustion of fuels.

Until recently, efforts of scientists were directed towards creation in a pipe of a flow moving with speed of the detonation wave. When counter velocities of flow and the detonation front are equal, the detonation wave can be stopped relative to the observer. For practical purposes, of the biggest interest are mixtures with high calorific value, possessing velocity of detonation of up to 3 km/sec. However, obtaining of stationary detonation in such mixtures is impossible in practice, inasmuch as stagnation temperature

at detonation Mach numbers considerably exceeds ignition temperature. Under these conditions, flow of mixture will be ignited on walls of pipe before detonation wave front. Recently, there have appeared a series of works in which there are undertaken attempts to realize a stationary detonation regime by roundabout means.

In 1958, J. A. Nicholls, E. K. Dabora, and R. A. Gealler realized stabilization of detonation wave in free supersonic stream of small dimension [1]. In these experiments, into stream of oxidizer there was injected fuel. Explosive mixture was separated from walls of pipe by layer of oxidizer. Upon exit of stream into atmosphere, there appeared a system of braking shock waves, which caused igniting of the mixture. Burning under these conditions occurred in a strongly impoverished mixture; therefore, such a process turns out to be unprofitable from the energy point of view.

Interesting investigations of detonation burning in supersonic flow were conducted by R. A. Gross and W. Chinitz [2]. In a wind tunnel flow of air was accelerated to Mach number of about three. In supersonic section of tunnel, on the walls there were installed wedges, creating a Mach shock configuration (Fig. 68). Hydrogen or methane was fed through intake duct located at a certain distance upstream from the critical section. Stagnation temperature of flow changed within wide limits. Starting from certain stagnation temperatures, addition of hydrogen into the flow led to change of observed configuration of fronts. Normal shock, seen in

Fig. 68. Configurations of fronts during detonation in supersonic flow according to Gross and Chinitz. a) flow without fuel; b) flow with fuel.

Fig. 68a, became a detonation shock, advanced forward and dimensions of it were increased. Interesting result of this work is discovery of hysteresis effect of ignition. With decrease of stagnation temperature of incident flow, temperature behind detonation shock dropped. Igniting of mixture occurred at a stagnation temperature of 1033°K, after which it was possible to lower it to 366°K. Under these conditions, temperature in reaction zone appeared considerably lower than temperature of ignition (894°K); nonetheless, detonation was maintained.

Extraordinarily low temperatures of reaction zone obtained in these works show that in processes of detonation phenomena of transfer play an important role, since shock wave in this case cannot serve as a source of ignition of the mixture.

Deficiency of such a method of realization of detonation regime as before is the small concentration of fuel; for these reasons, the given works are mainly of scientific interest.

R. I. Soloukhin [3] obtained regime of pulsating detonation in supersonic flow with stagnation temperature lying in the region related to large delays of ignition. Igniting of mixture occurred on detached shock appearing before a cylinder located in expanding part of detonation tube. During ignition there was formed detonation wave moving upstream until unloading from sides led to its attenuation. Shock remaining after damping of detonation traveled downstream to initial position, at which there occurred new ignition. Further, the process was repeated.

The impossibility of carrying out stationary detonation in supersonic flows of components mixed beforehand or being mixed in stoichiometric ratios led to attempts to obtain the necessary regime by other methods.

Development of theory of transverse detonation waves led to possibility of obtaining stationary regimes without preliminary acceleration of mixture to supersonic speed [4-6]. If we feed the mixture through holes located on periphery of annular detonation channel, then during initiation in such a channel of a detonation wave, it is possible to select rate of fuel feed and diameter of channel in such a way that during the time of a full revolution of the detonation wave, the mixture has time to be renewed.

Diagram of installation in which there was carried out stationary detonation of such type is shown in Fig. 69. Front of detonation wave constantly propagates in one direction along circumference of annular channel. Channel is a

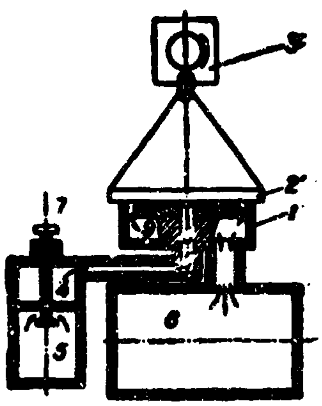

Fig. 69. Diagram of experiments on obtaining of continuous detonation in an annular gap. 1) detonation chamber; 2) plastic; 3) photorecorder; 4) precombustion chamber; 5) receiver for initial mixture; 6) receiver for exhaust gases; 7) valve; 8) intake "nozzle"; 9) exhaust chamber.

flat annular gap between two solid walls, one of which is a steel disk, the other — a disk of plastic. Exchange of gas mixture in annular channel is carried out through two slots parallel to channel and located on opposite sides of its cross section. Width of slots is somewhat less than width of channel. Supply of mixture was carried out from center to periphery of ring perpendicularly to direction of motion of detonation wave. Outer edge of ring has slanted profile for decrease of radial oscillations, which can lead to breakthrough of detonation wave into the center, and then into the bottle with the initial mixture. Experiments were produced with a stoichiometric oxyacetylene mixture. During use of less active mixtures, possibility of breakthrough into the center decreases.

Initiation of mixture in annular channel was carried out at one of points of circumference with help of spark discharge. If we do not apply special attachments, then detonation wave propagates from place of initiation simultaneously in various directions. On opposite side of ring waves collide; then, due to sharp increase of pressure, there can occur breakthrough of detonational wave through feeding slot into reservoir containing initial mixture. Problem of removal of reverse breakthroughs presents considerable technical difficulties and is solved by means of selection of special form of feeding nozzle and establishment of necessary pressure conditions. For preventing of appearance of counter detonation fronts near point of initiation, there was installed a closing device, completely covering cross section of entire channel. Synchronously with moment of explosion, the closing device of the channel started to open. Before detonation wave had time to complete a full revolution, the closing device opened completely and left the passage for circulation of the detonation wave free. Application of special explosive device ensured acceleration of opening of the shutter of the closing device of the order of $4 \cdot 10^6$ cm/sec^2.

Photographing of stationary detonation in annular channel on moving film was carried out through upper transparent wall with help of photorecorder located above the disk. Optical axis of photorecorder coincided with axis of annular channel, image of which was located within the limits of the film. During propagation of detonation wave front along circumference of disk, its image described on the film a cycloid. One of phototracings obtained in such a way is represented in Fig. 70.

Fig. 70. Phototracing of six-headed stationary detonation. All fronts move in one direction.

For analysis of physical processes accompanying stationary detonation, we concentrate attention to one of cross sections of annular channel. After passage of detonation wave front past this point, burning mixture starts to be driven back by the arriving fresh mixture toward periphery of ring. Initial mixture occupies the region of a wedge curved along the annular channel, with apex behind detonation wave front and with base coinciding with the following detonational front.

Let us assume that velocity of detonation is equal to D, outflow velocity of initial mixture is v and diameter of annular channel is d. Then time of full revolution of detonation wave equals:

$$t=\frac{\pi d}{D}. \tag{4.1}$$

Time between two consecutive moments of passage of detonation wave in the case when detonation consists of n heads revolving simultaneously along the circumference is equal to:

$$t_n=\frac{\pi d}{Dn}. \tag{4.2}$$

Considering speed of mixture along radius of channel to be constant, we obtain magnitude of projection Δl of every detonation front onto direction of radius:

$$\Delta l_n=\frac{\pi vd}{Dn}. \tag{4.3}$$

As experiment shows, quantity Δl_n apparently does not depend on v. Increase of v leads to proportional increase of number of

fronts n.

Stationary detonation occurs, as a rule, as many-headed, and only at the limit can there exist a single detonation front. Many-headed stationary detonation constitutes a very stable process. Number of fronts is established to be without limiting. This property is easy to understand if we remember that every front is a base of the above considered wedge, the magnitude of which for given mixture should remain constant. If there occurs accidental reduction of number of heads, then ahead of at least one of the remaining ones there will be attained a width of zone of fresh mixture exceeding the limiting width; this creates condition for appearance of new front and restoration of number of heads. In the reverse case, with appearance of a number of fronts greater than normal, there are formed weak, easily attenuating fronts, width of which is less than limiting width; this leads to reduction of number of fronts to a stable value.

Speed of propagation of stationary detonation depends on number of heads. In the limit, when only one head is formed, speed approaches the usual speed calculated according to Chapman and Jouget. With increase of number of heads, it drops to a magnitude of about 1.4 km/sec, approaching speed of sound in detonation products. In every experiment, pressure in feed reservoir decreases with outflow of gas mixture. Thus, on phototracings there was observed reduction of number of heads toward the end of the process and increase of speed of detonation.

Before every transverse wave in the considered channel, gas is divided by contact discontinuity GM into two regions (see Fig. 71). Let us assume that full width of channel is equal to h, width of region of unburned gas along radius is Δl. Let us construct two

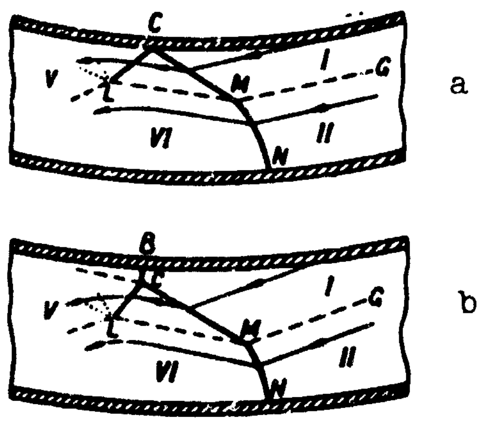

Fig. 71. Two variants of flow during stationary detonation.

control planes perpendicular to annular channel: one before detonation front and the second after the front at a distance where all parameters can be considered as uniform over the cross section. In reference to these two control surfaces, it is possible to write conservation equations for flux of mass, momentum and energy. Since flow rate of gas through transverse wave considerably exceeds flow rate through feed and exhaust slots on the section between control surfaces, the latter will be disregarded. We have

$$\left.\begin{aligned}&(h-\Delta l)\rho_2 D+\Delta l\rho_1 D=\rho_* u_* h;\\&(h-\Delta l)p_2+\Delta l p_1+(h-\Delta l)\rho_2 D^2+\Delta l\rho_1 D^2=\\&\qquad=p_* h+\rho_* u_*^2 h;\\&(h-\Delta l)\rho_2 D\left(i_2+\frac{D^2}{2}\right)+\Delta l\rho_1 D\left(i_1+\frac{D^2}{2}\right)=\\&\qquad=h\rho_* u_*\left(i_*+\frac{u_*^2}{2}\right).\end{aligned}\right| \tag{4.4}$$

where u is speed of gas relative to the considered wave; subscripts 1, 2, and * pertain respectively to unburned gas before front, unburned gas before front and gas after detonation wave front.

System of equations (4.4) can be transformed to usual form:

$$\left.\begin{aligned}&D\rho_0=\rho_* u_*;\\&p_0+D^2\rho_0=p_*+u_*^2\rho_*;\\&i_0+\frac{D^2}{2}=i_*+\frac{u_*^2}{2},\end{aligned}\right| \tag{4.5}$$

where there are introduced designations:

$$\rho_0=\frac{\Delta l\rho_1+(h-\Delta l)\rho_2}{h}; \tag{4.6}$$

$$i_0=\frac{\Delta l\rho_1 i_1+(h-\Delta l)\rho_2 i_2}{\Delta l\rho_1+(h-\Delta l)\rho_2} \tag{4.7}$$

and

$$p_0 = p_1 = p_2.$$

For calculation of speed of detonation, we will consider that after the front there is satisfied the usual condition of Jouget:

$$u_2^2 = c_2^2 = \frac{\gamma p_2}{\rho_2}. \qquad (4.8)$$

Then for ideal gas with constant ratio of heat capacities we obtain from equations (4.5) and (4.8) the formula

$$D^2 = I_0(\gamma^2 - 1) - \frac{\gamma p_1}{\rho_1} + \sqrt{\left[I_0(\gamma^2 - 1) - \frac{\gamma^2 p_1}{\rho_1}\right]^2 - \frac{\gamma^2 p_1^2}{\rho_1^2}}. \qquad (4.9)$$

Density and pressure are determined by the relations

$$\rho_2 = \frac{\gamma}{\gamma+1}\rho_1\left(\frac{p_1}{\rho_1 D^2} + 1\right); \qquad (4.10)$$

$$p_2 = p_1 + \rho_1 D^2\left(1 - \frac{\rho_1}{\rho_2}\right). \qquad (4.11)$$

Speed of detonation is more conveniently expressed in terms of heat of reaction Q, ratio $\alpha = (\Delta l/h)$ and temperatures of gas before front T_1 and T_2. We substitute I_1 and I_2 in equation (4.7) in the form

$$I_1 = C_p T_1, \quad I_2 = C_p T_2. \qquad (4.12)$$

Using (4.12), (4.7), and also equations of state of ideal gas and assuming constant molecular weight, after transformations of formula (4.9), we obtain

$$D^2 = \frac{C_p T_1(\gamma^2 - 1)}{1 + \alpha\left(\frac{T_2}{T_1} - 1\right)}\left[\alpha\frac{Q}{C_p T_1} + \frac{1}{\gamma+1} + \sqrt{\left(\alpha\frac{Q}{C_p T_1} + \frac{1}{\gamma+1}\right)^2 - \left(\frac{1}{\gamma+1}\right)^2}\,\right]. \qquad (4.13)$$

As $\alpha \to 0$ (increase of number of heads) $D^2 \to C_p T_2(\gamma - 1) = \gamma R T_2 = c_2^2$; for $\alpha = 1$, formula (4.13) determines usual Chapman-Jouget speed of detonation.

For clarification of structure of wave appearing during stationary detonation, there was performed photographing of process through a radial slot. Axis of photorecorder was fixed perpendicularly to plane of annular gap. Speed of rotation of drum of photorecorder was chosen in such a way as to compensate for motion of the photographed object. Photographs obtained thus reveal a triangular region of glow, one of the sides of which lies on inner circumference of ring. Vertex of triangle does not reach outer circumference of ring.

On the basis of obtained photographs it is possible to present two variants of diagram of flow in region of head. In Fig. 71a, there is shown one of variants. Here GM is boundary between fresh mixture (region I) and burning gas (region II); NMC is shock wave; at point M — break of shock wave at intersection of contact discontinuity. LC is reflected shock wave, after which chemical reaction mainly occurs. Region V is region of dispersion of detonation products after wave CL. Due to rotation of contact discontinuity, there occurs compression of gas in region VI, and thus there is realized a pressure head, due to which there exists shock wave MN. Second possible variant (see Fig. 71b) little differs from the first. Difference is that point C is able, in general, to move not along the wall, but at a certain distance from it; then between point C and the wall there will be formed transverse front BC.

Entire system of shocks (in both variants) is analogous to that observed during spin detonation in region of lower triple points (see Figs. 32 and 55). Shock MN is identified to that which is adjacent to transverse wave of part of the trail. Triple point C is formed by transverse wave and two shocks analogous to those observed during spin. As in the case of spin detonation, shock CL is reflected

from contact discontinuity ML in the form of a centered rarefaction wave. Luminous triangles revealed on phototracings apparently, correspond to region of burning gas between front CL and rarefaction wave. On phototracings of the process, front BC cannot be revealed, but, nonetheless, the second variant is more preferable, since in absence of front BC, after the system of shocks there do not appear temperatures necessary for igniting of the mixture.

If stationary detonation is initiated without covering of the channel, then there appear heads revolving in opposite directions, and tracings of the process appear as shown in Fig. 72. In this case there is hampered selection of magnitude of pressure at which there does not occur passage of flame into bottle containing the mixture.

Fig. 72. Phototracing of stationary detonation with heads revolving in opposite directions.

In process of investigations there was carried out stationary detonation under conditions when acetylene and oxygen were fed into chamber separately and mixing occurred in the annular channel.

Let us consider process of exchange of fuel mixture. Supply of mixture is produced through narrow hole from a bottle, where there is created pressure of 500-600 mm Hg, and occurs under conditions of critical outflow, for which expressions for speed and density of gaseous medium and also for flow rate of gas G have the form:

$$v_* = c_0\sqrt{\frac{2}{\gamma+1}}; \qquad \rho_* = \rho_0\left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}};$$
$$Q = v_*\rho_* S_c = S_c c_0 \rho_0\left(\frac{2}{\gamma+1}\right)^{\frac{1}{2}\frac{\gamma+1}{\gamma-1}}. \tag{4.14}$$

Let us designate cross section of exhaust slot S_2; then, considering that speed of sound in detonation products is close to D (for a many-headed stationary process), we have

$$\rho_{2*} = \frac{Q}{S_2 v_{2*}}; \quad v_{2*} = D\sqrt{\frac{2}{\gamma+1}};$$
$$\rho_{20} = \rho_{2*}\left(\frac{2}{\gamma+1}\right)^{-\frac{1}{\gamma-1}};$$
$$\rho_{20} = \frac{S_0 c_0 \rho_0}{S_2 D}. \tag{4.15}$$

For pressure in annular channel we have

$$p_2 = \frac{\rho_{20}D^2}{\gamma} = \frac{S_0 c_0 D \rho_0}{S_2 \gamma} \tag{4.16}$$

or

$$p_{20} = \frac{S_2 D}{S_0 c_0}p_0. \tag{4.17}$$

Regime of critical outflow in minimum cross section of feed nozzle can be fulfilled in the case when

$$p_2 < p_* = p_0\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}. \tag{4.18}$$

We substitute p_0 from (4.16) in equation (4.18):

$$p_{20} < p_{20}\cdot\frac{S_0 c_0}{S_2 D}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{4.19}$$

and finally obtain

$$\frac{S_2}{S_0} < \frac{c_0}{D}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}. \tag{4.20}$$

With nonsatisfaction of this condition, pressure will not satisfy condition (4.17).

Occurrence of stationary detonation process is accompanied by radiation of continuous sound with frequency nf, where n is number of heads, f is frequency of revolution of every head, magnitude of which is determined by relation

$$f=\frac{D}{\pi d}. \tag{4.21}$$

Till now we considered stationary detonation in an annular channel. It is also possible to imagine other methods of obtaining "stationary" detonation, process of combustion in which will be carried out by transverse waves, for instance between two planes, if supply of gas is produced through a large number of holes perpendicular to one of the planes, and removal is carried out through analogous holes in the other plane. In this case the entire flat region will be divided into triangles and polygons, continuously varying in shape as a result of displacement by the front. Dimensions of the cells depend on mixture composition and pressure according to the same laws which are applicable during determination of dimensions of cells of usual detonation.

In distinction from the yellow flame of usual burning, color of flame of stationary detonation is blue-green. Apparently, due to fast burning after shock wave, atoms of carbon do not have time to be recombined in big groups, due to which there is simultaneously attained more complete combustion of the explosive mixture.

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CHAPTER V

CERTAIN GENERAL CHARACTERISTICS OF DETONATION WITH TRANSVERSE WAVES

Definitions of Cyrillic Items in Order of Appearance

ж = J = Jouget

турб = turb = turbulent

шл = tr = trail

равн = eq = equilibrium

эфф = eff = effective

разр = rar = rarefaction

Experimental observations, and also theoretical conclusions of K. I. Shchelkin, R. M. Zaydel', and V. V. Pukhnachev (see Chapter III) permit us to conclude that classical smooth detonation front with one-dimensional zone of burning behind it is unstable under usual conditions, apparently for all gas mixtures. Instability leads to formation of transverse waves. Every transverse wave, in turn, constitutes a detonational complex, in most cases nonstationary. In this complex, the mixture is burned by a transverse front moving along the shock compressed gas, and by a break of the leading shock front appearing during flow around region of high pressure after the transverse front.

Transverse detonation waves appear and attenuate simultaneously with appearance and attenuation of detonation wave on the whole.

During usual multiple-front detonation (in other words, "pulsating," according to Yu. I. Denisov and Ya. K. Troshin), transverse waves periodically collide with each other; consequently, they are non-stationary. Stationary transverse waves can be observed only during spin detonation in round pipes and under special conditions of continuous detonation in flat annular channels (see Chapter IV). Structures of transverse waves during steady-state multiple-front detonation and spin detonation qualitatively are identical.

The continuation of transverse front into reaction products is the trail, which constitutes a shock wave, which is transformed with removal from the front into an acoustic wave. Direction of trail little deviates from perpendicular to the total detonation front. This means that average speed of transverse waves along front is close to speed of acoustic wave in products of reaction. The noted peculiarity of motion of transverse detonation waves becomes understandable after consideration of continuous ("stationary") detonation in an annular channel. In the latter case, structure of transverse wave differs by the fact that leading shock front, which preliminarily compresses and heats gas during usual detonation, is totally absent. Instead of it, there is the internal wall of the annular channel, through the slot in which there proceeds fresh mixture. Before every transverse wave, the layer of fresh mixture occupies only part of the section of the channel, and the width of this layer turns out to be insufficient for an independent detonation with local Jouget condition after its front to propagate through it.

However, here there turns out to be possible a stationary process in which igniting of narrow layer of fresh mixture is provided by a comparatively weak shock wave in the wider layer of hot products

of reaction adjacent on the side. Expansion of the burning gas, in turn, supports the leading shock wave in the hot layer. Such a process in a two-layered medium, without doubt, should be referred to detonation processes. At small magnitude of ratio of width of layer of initial mixture before wave to total width of channel, speed of wave with respect to walls is close to speed of sound in the layer of burning gas.

A similar mechanism of interaction is established, apparently, between transverse wave and trail during multiple-front detonation. Speed of transverse wave, in general, depends on ratio of width of transverse front proceeding through layer of compressed unreacted mixture to length of zone of reaction after it. If this ratio, which depends in turn on number of transverse waves per unit length of detonation front, were sufficiently great, speed of transverse front between head-on collisions would be determined by local Jouget condition after the transverse front. In reality, number of transverse waves per unit length of detonation front is established to be such, that between neighboring transverse waves new waves do not have time to form (due to instability of the smooth front). Thus, width of transverse fronts turns out to be comparable with the extent of the reaction zone after them, and in process of burning, gas is expanded to the sides. Consequently, work of expansion of burning gas after transverse front goes not only to support the transverse front itself, but also the adjacent part of the trail and the "break" in the leading shock front.

It is necessary to expect that during multiple-front detonation, transverse fronts, as a rule, are smooth; i.e., on them there are no longer the small transverse perturbations revealed during spin detonation of mixture $2H_2 + O_2$. Otherwise, zone of reaction after

transverse front would be considerably less than its width, and the front would propagate according to Jouget.

Let us now discuss question about influence of transverse waves on average characteristics of medium after front, and the Chapman-Jouget condition. Presence of transverse waves makes the state of gas in every plane parallel to the front nonuniform; therefore, one-dimensional theory of detonation presented in Chapter I needs corrections, which would consider non-one-dimensional effects. Apparently, the first serious attempt in this direction was made by D. R. White [1]. Interference photographs of reaction zone in detonation wave obtained by him showed the presence of strong heterogeneities of density near the front, which with increase of distance from the front gradually disappear. Without investigating causes of appearance of heterogeneities and their structure, White describes them in the first approximation as isotropic turbulence, although he indicates that in reality isotropism does not exist. Actually, nonstationary motion of transverse waves and presence in structure of each of them of contact discontinuities with great difference in tangential velocities should lead to development of turbulence after the front. However, in front layer with thickness of the order of the width of transverse fronts (we will call it subsequently the "layer of transverse fronts"), heterogeneities of the media are connected basically not with turbulence, but with motion of transverse waves themselves. After this layer there have to be considered turbulent pulsations of the medium, which are more or less isotropic with respect to directions, as well as ordered transverse motions connected with the trails.

In layer of transverse fronts, amplitude of pulsations of velocity in order of magnitude is close to speed of sound in Chapman-Jouget state c_J. And since basic scale of heterogeneity in the front

is a, then as the criterion of development of turbulence there should serve Reynolds number $R = (c_J a\rho/r)$.

For mixture $C_2H_2 + 2.5\ O_2$, $R \simeq 2000$, i.e., is close to critical; for other, less active mixtures, for instance $2H_2 + O_2$ and $2CO + O_2$, Reynolds number is considerably larger (due to large a at that same density), and turbulence undoubtedly is developed. Apparently, only in mixtures comparable in activity with $C_2H_2 + 2.5\ O_2$ does turbulence not occur.

Oscillograms of pressure in mixture $2CO + O_2$ with small additions of H_2 given in Chapters II and III do not make it possible to clearly reveal turbulent pulsations of pressure against the background of characteristic noises of the pickups, although their resolving power is sufficient. On the basis of these oscillograms, it may be concluded that amplitude of turbulent pulsations of pressure Δp_{turb} in any case is not more than 1/5 of amplitude of pressure in the trails Δp_{tr}. Since $\Delta p_{turb} \sim \rho(\Delta u_{turb})^2$ and $\Delta p_{tr} \sim \rho \Delta u_{tr} c_J$, then, considering $(\Delta p_{turb}/\Delta p_{tr}) \sim (1/5)$ and $\Delta u_{tr} \sim (1/3)c_J$, we obtain $\Delta u_{turb} \sim (1/4)c_J$; i.e., although turbulent pulsations of pressure are certainly less than in the trails, pulsational velocity of particles which is connected with them, and consequently also kinetic energy, can be of the same order as in the trails.

Following White, we will write laws of conservation of flux of mass, momentum and energy on control surfaces parallel to the front which are constructed through the initial state of the mixture (subscript 0) and reaction products (without number index) in a system of coordinates motionless with respect to the front:

$$
\left.
\begin{aligned}
\rho_0 D &= \frac{1}{S}\int\limits_S \rho u_z dS;\\
p_0 + \rho_0 D^2 &= \frac{1}{S}\int\limits_S (p + \rho u_z^2)\, dS;\\
\rho_0 D\left(I_0 + \frac{D^2}{2}\right) &= \frac{1}{S}\int\limits_S \rho u_z\left(\frac{u^2}{2} + I\right) dS,
\end{aligned}
\right| \qquad (5.1)
$$

where axis z is perpendicular to middle position of front and coincides with direction of velocity of undisturbed flow;

I — enthalpy of gas (including chemical energy);

S — area of integration, containing large number of transverse perturbations in gas, or equal to area of cross section of detonation channel (for small number of transverse waves).

Relations (5.1) are true only on the assumption that integrals in right sides do not depend on time.

Let us introduce designations:

$$
\left.
\begin{aligned}
&\bar{\rho} = \frac{1}{S}\int\limits_S \rho dS; \quad \bar{p} = \frac{1}{S}\int\limits_S p dS;\\
&\bar{u}_z = \frac{\int\limits_S \rho u_z dS}{\int\limits_S \rho dS}; \quad u_z' = u_z - \bar{u}_z;\\
&\overline{u_z'^2} = \frac{\int\limits_S \rho u_z'^2 dS}{\int\limits_S \rho dS}; \quad \overline{u_\perp^2} = \frac{\int\limits_S \rho u_\perp^2 dS}{\int\limits_S \rho dS};\\
&\bar{I} = \frac{\int\limits_S I \rho dS}{\int\limits_S \rho dS}; \quad I' = I - \bar{I}.
\end{aligned}
\right| \qquad (5.2)
$$

Here $u_\perp$ is component of velocity in direction perpendicular to axis z. All quantities have usual meaning: $\bar{\rho}$ and $\bar{p}$ respectively are average density and pressure over cross section; $\bar{u}_z$, $\overline{u_z'^2}$, $\overline{u_\perp^2}$, $\bar{I}$ are mean-mass values of the corresponding quantities.

Using (5.2) and separating from enthalpy the chemical energy Q by means of equality

$$\bar{I} - I_0 = \overline{i(p,\rho)} - \overline{i_0(p_0,\rho_0)} - Q,$$

we can transform equations (5.1) to form analogous to (1.1)-(1.3):

$$\rho_0 D = \bar{\rho}\bar{u}_z; \tag{5.3}$$

$$p_0 + \rho_0 D^2 = \bar{p} + \bar{\rho}\bar{u}_z^2 (1 + \alpha); \tag{5.4}$$

$$i_0(p_0, \rho_0) + \frac{D^2}{2} = \overline{i(p,\rho)} + \frac{\bar{u}_z^2}{2} - (Q - \Delta), \tag{5.5}$$

where

$$\alpha = \frac{\overline{u_z'^2}}{\bar{u}_z^2},$$

$$\Delta = \frac{\int_S \rho u_z' I' dS}{\bar{\rho}\bar{u}_z \cdot S} + \frac{3}{2}\overline{u_z'^2} + \frac{1}{2}\overline{u_\perp'^2} + \frac{\int_S \rho u_z' (u_z'^2 + u_\perp'^2) dS}{2\bar{\rho}\bar{u}_z \cdot S}. \tag{5.6}$$

Corresponding relationships of White differ from those given here by the fact that in expression (5.6) for Δ, in virtue of the assumption about isotropic turbulence, first and last terms are equal to 0, and $\overline{u_\perp^2} = 2\overline{u_z^2}$. Last term indeed is always small as compared to the others, when $\alpha \ll 1$; the first, however, near the pulsating shock front, as it is simple to estimate, in absolute value can even exceed subsequent terms. Quantitative estimate of change of first term with increase of distance from front is difficult, but sufficiently obvious: with development of turbulence behind layer of transverse fronts, when pulsations of particles with identical sign of I' become equiprobable in directions +z and -z, it rapidly approaches 0. Under the condition that amplitude of pulsations of front along axis z is much larger than thickness of strictly the shock transition (which is always satisfied), equations (5.3)-(5.6) also describe transition through layer containing protuberances and depressions of the leading shock front. In this layer of protuberances and depressions, α attains value close to 1; therefore, it is necessary to consider also the last term in the expression for Δ.

Designating $(\overline{p}/p_0) = \pi$ and $(\overline{\rho}/\rho_0) = \sigma$, from equations (5.3) and (5.4) we will obtain

$$\pi - 1 = \frac{\rho_0 D^2}{p_0}\left[1 - \frac{1}{\sigma}(1 + \alpha)\right], \tag{5.7}$$

and using also equation (5.5), in which there is set $i_0(p_0, \rho_0) = [\gamma/(\gamma - 1)](p_0/\rho_0)$ and $\overline{i(p, \rho)} = [\gamma/(\gamma - 1)](\pi/\sigma)(p_0/\rho_0)$, we will come to the "corrected" Hugoniot relationship

$$\pi = \frac{\sigma + \sigma\frac{\gamma-1}{\gamma}\frac{\rho_0}{p_0}(Q-\Delta) - \frac{\gamma-1}{2\gamma}\frac{\sigma+1}{1-\frac{\sigma}{\sigma-1}}}{1 - \frac{\gamma-1}{2\gamma}\cdot\frac{\sigma+1}{1-\frac{\sigma}{\sigma-1}}}. \tag{5.8}$$

The most important distinction from purely one-dimensional flow here is that states inside stationary zone described by averaged are not located along a straight line if α changes, as one may see from equation (5.7).

In Fig. 73 there are depicted possible steady-state detonation processes in plane $(1/\sigma, \pi)$. Here H_0 and H_{eq} are respectively shock and equilibrium detonation adiabats for one-dimensional flow. At given speed of detonation, family of straight lines along which α = const is a pencil of straight lines passing through the point with coordinates $(1/\sigma) = 0$, $\pi = 1 + (\rho_0 D^2/p_0)$, where the straight line for $\alpha = 0$ passes through point of initial state (classical straight line of Michelson). If speed D is given, then change of

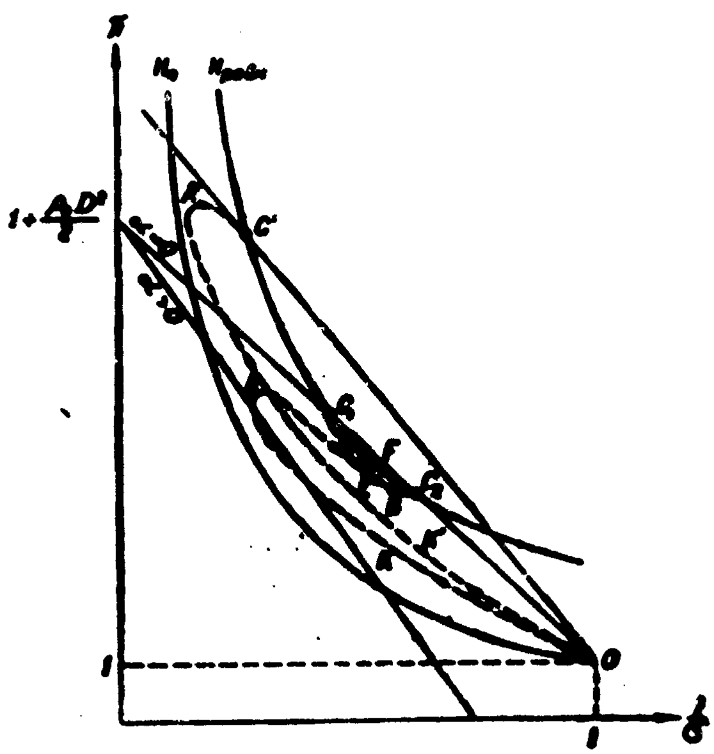

Fig. 73. p, v-diagram of steady-state detonation processes taking into account pulsations.

state inside detonation zone is completely determined by change of parameter α and effective quantity of heat released:

$$Q_{eff} = Q - \Delta.$$

From equality (5.3)-(5.5) there can be obtained relationships analogous to (1.21)-(1.23), which express dimensionless average density and pressure π, and also number $M = \frac{\bar{u}_1}{c} = \frac{\bar{u}_1}{\sqrt{\gamma \bar{p}/\bar{\rho}}}$ as a function of parameters α and Q_{eff} at given speed D.

$$\sigma_{1,2} = \frac{c_0^2 + \gamma D^2 \pm \sqrt{(D^2 - c_0^2)^2 - 2\alpha\gamma D^2\left[2c_0^2 + (\gamma - 1) D^2\right] - 2(\gamma - 1) D^2 Q_{eff}(1 + \gamma + 2\alpha\gamma)}}{2c_0^2 + (\gamma - 1)(D^2 + 2Q_{eff})}; \quad (5.9)$$

$$\pi_{1,2} = 1 + \gamma \frac{D^2}{c_0^2}\left[1 - \frac{1}{\sigma_{1,2}}(1 + \alpha)\right]; \quad (5.10)$$

$$M_{1,2}^2 = \frac{1}{\gamma\left[\sigma_{1,2}\left(1 + \frac{c_0^2}{\gamma D^2}\right) - (1 + \alpha)\right]}. \quad (5.11)$$

The two signs in equality (5.9) correspond to two intersection points of straight line (5.7), on which D = const and α = const, with Hugoniot adiabat (5.8), on which Q_{eff} = const and α = const. Equality (5.9) shows also that in stationary (with respect to introduced average quantities) zone effective quantity of heat Q_{eff} cannot exceed a certain value

$$Q_{eff}^* = \frac{(D^2 - c_0^2)^2 - 2\alpha\gamma D^2\left[2c_0^2 + (\gamma - 1) D^2\right]}{2(\gamma - 1) D^2 (1 + \gamma + 2\alpha\gamma)}, \quad (5.12)$$

at which the subradical expression becomes zero. At the point with coordinates $\sigma = \sigma(Q_{eff}^*)$ and $\pi = \pi(Q_{eff}^*)$, obviously, there occurs contact of straight line α = const and Hugoniot adiabat for the same α and $Q_{eff} = Q_{eff}^*$ = const. Calculations show that at this point

$$M^*(Q_{eff}^*) = \frac{1}{1 - \alpha\gamma}, \quad (5.13)$$

i.e., averaged Mach number at the point corresponding to highest

possible release of heat in stationary flow is less than unity if $\alpha > 0$.

Curve $O'K'A'C'$ in Fig. 73 depicts behavior of change of averaged magnitudes of pressure and density in supercompressed detonation wave supported by a piston. Section $OK'A'$ corresponds to transition in layer of protuberances and depressions of leading front.

From relationship (5.8) it is clear that Hugoniot adiabat for any fixed values of Q_{eff} and $\alpha > 0$ lies above Hugoniot adiabat for the same Q_{eff} and $\alpha = 0$. Inasmuch as in region of maximum π, $Q_{eff} > 0$ (mainly due to chemical reaction in the protuberances) and $\alpha > 0$, maximum average pressure in detonation wave is always smaller than on plane shock wave front propagating with the same velocity. Transition through pulsating detonation front in many respects resembles transition through a plane detonation front with strong viscosity (see Fig. 8). In connection with the fact that in supercompressed wave length of column of gas before piston can be assumed to be sufficient for damping of all pulsations; final state of gas in absence of losses will be depicted by point C^1 on the equilibrium adiabat.

Most important here is the question about finding of the regime of self-supported detonation. The exceptional constancy of speed of detonation known from experiment means that even in nonuniform flow at a certain constant distance from the front there is a surface on which time average velocity of perturbations moving in the direction of front is equal to time average velocity of particles. Therefore, nonstationary rarefaction wave, if it adjoins this surface, cannot pass through it and weaken the detonation front. Every element of such a surface pulsates near a certain average position with frequencies corresponding to frequencies of motion of the trails and turbulent

pulsations. The plane passing through middle position of the considered surface, just as in the absence of pulsations, is naturally called the Jouget plane. To the Jouget plane, in general, there can adjoin the rarefaction wave, as well as the stationary supersonic zone.

In turbulent flow, speed of perturbations does not coincide with the root-mean-square velocity of sound $\bar{c} = \sqrt{\gamma \bar{p}/\bar{\rho}}$ introduced earlier into Mach number. In system of coordinates moving together with detonation wave, local velocity of perturbations in direction $-z$ is equal to $(c - u_z)$. It is clear that rarefaction wave front will propagate the fastest of all through those particles of the medium in which this difference is maximum, and will cause drop of pressure in other particles, adjacent on the side, with smaller value of $(c - - u_z)$.

Velocity of perturbations relative to turbulent medium obviously is larger than average speed of sound, and plays the same role as "frozen" speed of sound in a relaxing medium. It coincides with velocity of rarefaction wave front, which carries infinitesimal changes of pressure. Regions of rarefaction wave with drop of pressure noticeable in practice propagate relative to the medium with a certain smaller velocity v_{rar}. Namely, this last velocity should be included in the condition in the Jouget plane:

$$\frac{\bar{u}_z}{v_{rar}} = 1. \tag{5.14}$$

Apparently, quantity v_{rar} always lies between average speed of sound and velocity of perturbations. Our subsequent conclusions are based on the assumption that in plane after detonational front, where $Q = Q^*$, $\bar{u}_z = v_{rar}$. Considering (5.13), we see that this assumption is equivalent to the following:

$$v_{рез} > \frac{\bar{\epsilon}}{1+\epsilon\gamma},$$

the validity of which does not cause doubt.

In Jouget plane, where (5.14) is satisfied, value of M differs from 1 by a magnitude of the order of $\sqrt{\alpha}$; therefore, Jouget condition for detonation wave with turbulent zone in terms of M and α will be rewritten in the form

$$M = 1 + \beta_1\sqrt{\alpha}, \qquad (5.14')$$

where β_1 is a numerical coefficient of the order of unity.

For propagation of self-supported detonation wave with constant speed, it is necessary that value of M determined by equality (5.14') be attained in stationary flow.

In the presence of transverse waves, combustion of mixture occurs in the narrow front layer of the detonation wave which contains transverse fronts. Here there is released the basic quantity of chemical energy Q, which after the shell of transverse fronts apparently changes little. It is essential, however, that toward the end of the layer of transverse fronts the value of α still be sufficiently great (although considerably less than 1).

Relationship (5.9), describing change of σ in process of release of basic quantity of heat, should be taken with the "plus" sign before the radical. Equalities (5.9)-(5.13) show that for achievement of $M > M(Q^*)$ it is necessary that the radical pass through zero and change "plus" sign to "minus." Let us separate from effective heat the term connected with pulsations along z (see (5.6)) by means of equality

$$Q_{эфф} = Q' - \frac{5}{2}\alpha\frac{D^2}{\sigma^2}.$$

Equating subradical expression to zero and disregarding small terms of the order of $D^2\alpha^2$, and also c_0^2 as compared to D^2, we will obtain

$$D^2 - 2(\gamma^2 - 1)Q' - \alpha\gamma^2 \frac{5 - 3\gamma}{\gamma + 1} D^2 = 0. \qquad (5.15)$$

It is essential that term containing α be contained in last equality with negative sign. (Sign of this term remains negative while numerical coefficient of $\alpha(D^2/\sigma^2)$ in the next to last equality is less than $\gamma/(\gamma - 1)$).

It is obvious that during approach to Jouget plane α monotonically decreases, Q' can increase monotonically, as well as pass through maximum (due to peculiarities of mechanism of reaction) with subsequent decrease.

Since in self-supported stationary detonation wave equality (5.15) should be satisfied at a certain interior point, where $\alpha = \alpha^* > 0$, then subsequent decrease of α can lead to growth of the subradical expression if Q' no longer increases or increases sufficiently slowly. Then with change of sign before radical and further growth of σ, value of M will grow. Let us show that it attains then the magnitude determined by condition (5.14').

Let us designate $\alpha = \alpha^*$ at $Q_{eff} = Q^*_{eff}$, and place (5.15) in (5.9); then we place (5.9) with the "minus" sign in (5.11), and then, again disregarding c_0^2 in comparison with D^2 and terms of the order of α^2 and $\alpha^{3/2}$, after transformations we will obtain

$$M^2 = \frac{1}{1 + \alpha^*\gamma + \gamma(\alpha^* - \alpha) - 5\gamma^2(\gamma - 1)(\alpha^* - \alpha) - \sqrt{(5 - 3\gamma)(\gamma + 1)(\alpha^* - \alpha)}}, \qquad (5.16)$$

where $1 \gg \alpha^* > \alpha > 0$.

Since with decrease of α expression (5.14') tends to unity, and (5.16) at $\gamma < 5/3$ tends to a quantity larger than unity, it is clear that in a certain plane (point B in Fig. 73), where $\alpha^* > \alpha > 0$, value of M attains the magnitude $1 + \beta_1\sqrt{\alpha}$. This plane will be the Jouget plane, since perturbations cannot penetrate through it in the

rection of the front.

After the Jouget plane M continues to grow, and flow becomes upersonic relative to detonation front. (By speed of sound, here t is necessary to understand effective, i.e., true speed of sound). If the stationary zone is continued up to total damping of turbulence and trails, then end point C_2 obviously will lie on equilibrium adiabat below point of tangency F to it of the straight line of Michelson.

Demonstration of the uniqueness of the regime of self-supported detonation can be approached in the following way: Let us consider series of stationary supercompressed regimes (supported by a piston) for which speed of detonation D gradually decreases. It is clear that at sufficiently large D subradical expression in equality (5.9) is everywhere positive, and that in reaction zone the root should be taken with the "plus" sign. Passing onto regimes with gradually decreasing speeds D, we will reveal that on a certain curve $OKAEC_1$ describing the process (see Fig. 73), subradical expression for the first time will become zero at a certain point E (we do not consider vanishing at two or more points as an exceptional case). It is obvious that at remaining points subradical expression remains positive, since we approached the considered position from the region where it was everywhere positive. But after point E the root can change sign, and curve OKAE is branched into two: EC_1 and EC_2. Lower branch EC_2 will correspond to "minus" sign before the root. For the case when after point E there changes only α, it was shown above that on curve $OKAEC_2$ at a certain point B velocity of flow becomes speed of sound relative to the front; consequently, the corresponding regime will be self-supported. From equalities (5.9)-(5.13) it

follows that along curve $OKAEC_1$ velocity of flow is everywhere subsonic and that the corresponding regime can be realized only in the presence of a supporting piston. Thus, pressure and density, which attain at point E minimum value, then grow again, nearing values determined by the upper intersection of Michelson straight line with the equilibrium adiabat.

Stationary detonation process with smaller velocity D than on curve OKAE is impossible, since in this case after becoming zero, the subradical expression becomes negative.

Thus, we arrive at the conclusion that the unique self-supported stationary regime of detonation is that which is depicted by curve $OKAEC_2$.

Position of point E inside detonation zone is determined by character of change of Q_{eff} and α. Above we assumed that at point E, $\alpha = \alpha^* > 0$, and that Q' attains finite value. We will briefly consider two other important cases.

If heat released in process of reaction passes through maximum and then decreases, nearing equilibrium, the point can appear on the other side of the equilibrium adiabat.

In this case process will not differ from that considered, except that conditions of transition to supersonic flow are additionally eased.

There is possible the case when point E is reached only at an infinitely large distance from the front, where all pulsations attenuate. Then it will be on the equilibrium adiabat and will coincide with the Chapman-Jouget point (which is apparently equilibrium, since after an infinitely extended reaction zone it is natural to assume also an infinitely extended rarefaction wave, which propagates relative to the gas with equilibrium speed of sound).

From (5.15) we obtain that velocity of detonation determined by equality

$$D^2 = \frac{2(\gamma^2 - 1)Q'}{1 - \alpha^2\gamma^2\frac{5 - 3\gamma}{\gamma + 1}}, \qquad (5.17)$$

can appear larger than the velocity of detonation calculated in the absence of turbulent pulsations from the condition of tangency to the equilibrium adiabat. In experiments of D. R. White on the mixture $2H_2 + O_2 + 2CO$, with increase of initial pressure it was observed that measured velocity somewhat exceeded velocity calculated from the equilibrium condition of Jouget. Furthermore, velocity of gas after detonation front appeared supersonic. (It is necessary to note that the excess of observed velocity over calculated velocity and supersound after the front can be explained even without taking into account pulsations on the basis of one-dimensional theory of Zel'dovich, which was presented in Chapter I, if we assume that release of heat passes through a maximum). If in the plane where there is satisfied condition (5.15) a sufficiently large fraction of chemical energy is still contained in kinetic energy of the trails, then velocity of detonation will be less than that calculated from one-dimensional theory; this is always the case during one-headed spin detonation. Additional lowering occurs due to losses, which we did not consider here.

Estimate of energy contained in trails and turbulent pulsations on the basis of oscillograms of pressure shows that near transverse fronts it is about 1% of the chemical energy released in the detonation wave, and rapidly decreases with increase of distance from the front. Therefore, deviations of velocity of detonation from that calculated for the one-dimensional zone from the equilibrium condition of Jouget are small.

Much larger corrections are given to mean values of pressure and density by consideration of pulsations. Above it was shown that maximum average (over cross section) pressure in detonation wave is less than that after a plane shock front propagating with velocity of detonation. Experiments of S. M. Kogarko [3], in which maximum of measured average pressure always turns out to be between pressures after plane shock front and at the Chapman-Jouget point (without approaching either one), confirm this conclusion. According to data of G. B. Kistiakowsky and P. H. Kidd [4], maximum averaged density in direction parallel to front is also approximately 1.5 times less than after plane shock wave.

According to measurements of D. R. White, the pressure after Jouget plane in detonation wave is less than that calculated from Chapman-Jouget equilibrium condition. (Our measurements, described in Chapter III, are not exact enough to warrant such a conclusion). R. E. Duff and H. T. Knight obtained as a result of precise experiments also densities which were too low, for explanation of which they propose to consider composition and vibrational degrees of freedom of molecules [5] to be frozen in the Jouget plane. On the basis of the above results, these facts are explained, since point C_2 (see Fig. 73), and possibly point B which are separated by a small interval of change of α, but by a larger distance after the detonation front, lie below and to the right of the point of tangency F to the equilibrium adiabat. Point C_2, in general, must not be determined by any of the frozen conditions of Chapman-Jouget; coincidence can only be accidental.

Basic characteristic dimension of detonation front is average dimension of cells a, formed by the intersecting transverse waves. Structure of transverse waves in all mixtures can be considered in

first approximation to be geometrically similar. This assumption is based on the fact that trace imprints of transverse waves on sooty walls of tubes are qualitatively identical for mixutres strongly differing in chemical properties ($2CO + O_2$ and $2C_2H_2 + 5O_2$). In such a case, all other characteristic dimensions, for instance average width of transverse fronts, are proportional to a. If all transverse waves have structure of I-st type (see Chapter III), then combustion of mixture occurs in a layer whose thickness is determined by dimension of transverse fronts, i.e., of the order of 0.2a. Assuming that in three-dimensional detonation front there are also formed transverse waves with structure of II-nd type, we obtain effective thickness of detonation front, approximately equal to a. This is confirmed by comparison of dimensions of cells in various mixtures (see Table 4) with experimental measurement of effective thickness of detonation front by Ya. B. Zel'dovich, S. M. Kogarko, and N. N. Simonov.

Average dimension of cells in detonation front depends on reactivity of mixture. If behavior of chemical reaction can be described by an equation of form (1.19), then, in absence of transport phenomena, dependence of width of reaction zone after the plane of the shock front on temperature and pressure is determined basically by the factor

$$\frac{e^{\frac{E}{RT}}}{p^{m-1}},$$

where E — effective activation energy;

m — order of total reaction with respect to pressure;

T and p — respectively temperature and pressure after the shock wave [2].

During multiple-front detonation, extent of reaction zone after transverse front is of the order of width of the actual front, and

consequently is proportional to a.

The idea of use of experimental dependences of average dimension of cells on initial parameters of mixture seems attractive for production of data about kinetics of chemical reaction [6]. It is most simple by this method to study the influence of small gas additions on kinetics, which strongly change chemical reaction rate. In this case velocity of detonation, composition of reaction products, speed of sound in products and, consequently, temperature and pressure after transverse fronts practically remain as before, and by change of dimension of cells it is possible to judge about change of rate of reaction. If speed of detonation and, consequently, temperature after transverse front do not depend on initial pressure (for instance, in mixture $H_2 + Cl_2$), then, by knowing dependence of a on p_0, we can determine order of reaction m. According to experimental measurements (see Chapter III), dimension of cells in various mixtures changes approximately in inverse proportion to initial pressure; this corresponds to reaction of the second order. However, the exponent in expression (3.4) does not determine exact value of m, since during change of pressure in given mixtures velocity of detonation does not remain strictly constant.

However, determination by this method with any degree of reliability of the effective activation energy is impossible, in view of the strong change of temperature after the transverse fronts between their successive collisions. During one-headed spin detonation, there also exists uncertainty of temperature, due to the presence of small-scale perturbations on the transverse front itself. Furthermore, in process of support of reaction after the transverse wave in hydrogen-containing mixtures, an essential role is apparently played

by diffusion of active centers of H. In this case, dependence of width of reaction zone on temperature after the front no longer is determined by factor $e^{(E/RT)}$. Let us refer to experiments of R. A. Gross and W. Chinitz [7], who observed stable ignition of the mixture after the shock wave under conditions when temperature in zone of reaction was everywhere lower than temperature of adiabatic self-ignition.

On the basis of ideas about transverse waves, it is possible to explain the limit of spin detonation in pipes without using the loss factor. Width of transverse front during spin detonation constitutes a fully definite part (1/8-1/10) of length of the circumference. If in tubes of fixed diameter we gradually decrease initial pressure of mixture, then ratio of width of transverse front to length of zone of reaction after it will decrease. For a value of this ratio smaller than a certain critical value, spin detonation will become impossible, since transverse detonation front will attenuate due to strong discharge to the sides. The same will occur if we approach the limit by any other method: by decrease of diameter of tube or change of composition of mixture.

Losses affect limit of spin detonation only indirectly: they decrease speed of detonation, as a consequence of which temperature after transverse front drops and zone of reaction is extended. Experiments show [8] that in smooth tubes, after damping of spin detonation, stable detonation is absolutely impossible. Damping of transverse wave leads to sharp lengthening of zone of chemical reaction after shock front, and the impossibility of the nonspin regime is due exclusively to thermal and mechanical losses on walls of the tube.

Authors observed cessation of detonation near the limits by placing in the inside of the tube a rib with height of about (1/5)d.

In analogous experiments of V. A. Bone and others [9, 10], height of rib was smaller, and detonation did not attenuate. It is also possible that in experiments of Bone conditions of detonation were somewhat far removed from the limits.

In very rough tubes, K. I. Shchelkin [11] observed widening of limits of detonation as compared with smooth tubes, but this is due to change of the mechanism of ignition: in the presence of pronounced roughness, ignition occurs as a result of reflection of shock wave from projections of the wall. Phenomena in layer adjacent to the wall apparently also play an important role for stabilization of spin detonation in relatively smooth tubes.

Thus, ideas concerning transverse detonation waves developed in the present book supplement the theory of detonation phenomena. Existing experimental material shows that transverse waves accompany any detonation in gases from the moment of its appearance until damping.

There are known experiments in which there are also revealed analogous phenomena during detonation of condensed explosives. Thus, T. Urbanskiy [12] observed periodic structure of glow on photoscans of detonation of cylindrical charges of mixture of trotyl with ammonium nitrate. A. N. Dremin and O. K. Rozanov [13] obtained a network of brightly luminous lines by photographing detonation front in liquid mixture of nitromethane with acetone.

Obviously, transverse waves can appear only in those cases when they strongly reduce zone of chemical reaction after the shock wave. In single crystals, as it is known, temperature after front of shock wave propagating with detonation speed is completely insufficient for initiation of chemical reaction. Therefore, it is possible

assume that detonation front in single-crystal explosives also contains transverse waves. It is natural that experimental investigations in this direction will be of great interest.

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